Macroscopic and Microscopic Variation of Iron and High Carbon Steel Production in the Southern Highlands of Tanzania

Edwinus Chrisantus Lyaya

University College London

Institute of Archaeology

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Declaration

I, **Edwinus Chrisantus Lyaya**, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed:

Date:

Abstract

One essential feature of African iron production process is that it is greatly variable in culture and technology. The early research focused on some themes: origins, culture, and how iron was produced, which were investigated using archaeological, ethno-archaeological, and experimental methods. The purpose of this thesis was to examine the relationship between macroscopic and microscopic variation of iron and steel production in the southern highlands of Tanzania. I used field methods: ethnographic inquiry, surface and sub-surface survey, mapping, and excavation; and laboratory analytical techniques: firing, optical and electron microscopy, microanalysis, and X-ray fluorescence to investigate the research theme.

The results indicate that there is a strong relationship between macro- and microscopic variation of iron and steel production in terms of the use technical ceramics with good refractory qualities, the presence of the three stage process in Ufipa and Unyiha, involving a refining stage between the smelting and smithing stages; the liquid slag handling techniques, the reduction efficiency, and the nature of the final products: soft iron and carbon-rich steel. Although there are macroscopic data on the use of forced- and natural-draft furnaces in the region, it is difficult to microscopically verify the air supply mechanisms in the region.

This work recommends that in order to avoid the confusion on the three stage process and relationship between macro- and microscopic variation in iron and steel production, the role of matrix and provenance should be given due weight as laboratory analyses.

Table of Contents

List of Figures

List of Tables

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1. Introduction: Introducing the Research Question

1.1 Preamble

Archaeology is the study of human *culture* mainly through cultural remains (organic and inorganic) or cultural phenomena. Systematic research on the Stone Age (stone artefact production, rock art) of Africa started earlier (*cf*. Mabulla 1996) than on the metal production process (*cf*. Mapunda 1995b; Chirikure *et al*. 2009). Generally, there were more researchers working on Stone Age technology than researchers working on metal production techniques, probably because of the interest to understand the earliest human cultural origins in Africa, and iron was considered to be recent, degenerate, and derived. Today the ratio of Stone Age specialists to metal production specialists *working* at the University of Dar es Salaam (UDSM) in Tanzania is 4:1 (*cf*. Masao 1979; Mapunda 1995a, 1995b; Mabulla 1996; Kessy 2005; Bushozi 2011). One problem of the research imbalance is that the Stone Age culture and technology of Tanzania is better known than the metal production processes of Tanzania, because until recently the latter was *terra incognita* (for details, see Chapter 2; see also Killick 2009: 407). To rectify the problem, this work focuses on the metal production process in the southern highlands of Tanzania. The metal production process was important for the communities in terms of agriculture, fishing, trade, and for symbolic purposes (e.g. Miller 2002; Killick 2004a; Chirikure 2007; Mapunda 2010). Archaeologists are increasingly becoming aware of the significance of macroscopic variation of African iron and steel production including, but not limited to, the impressive ethnographic evidence for diversity in furnace designs (*cf*. see Haaland 1985; Sutton 985; Pole 1985; Celis 1987; Killick 1987; van Schalkwyk 1987; Davison and Mosley 1988; Mapunda

2010; Burka 2012). The southern highlands of Tanzania are well endowed with ethnographic and archaeological evidence of the great variation in furnace designs of the metal production process. Little is known however on whether the macroscopic variation of the smelting and refining furnace designs are related to microscopic variation of iron and steel production in the region. This thesis examines the relationship between macro- and microscopic variation of iron and steel production. To this end, a microscopic laboratory-based approach is adopted, because previous studies in the southern highlands mostly concentrated on macroscopic approaches.

1.2 Research on Metal Production Process in Africa

The early and indeed, most of the 20th century research in archaeometallurgy in sub-Saharan Africa was dedicated to the investigation of three topics: (1) the origins and history of iron production (e.g. Peake 1933; Sassoon 1963; Trigger 1969; Tylecote 1975; Schmidt 1983; Kense 1985; Killick 2004a; Alpern 2005; Holl 2009; Chirikure 2010), (2) the techniques of iron metal production (e.g. Friede and Steel 1986b, 1988; David *et al*. 1989; Killick 1990; Schmidt 1997a; Barndon 2004), and (3) the symbolism and rituals of iron and steel production (e.g. Collett 1993; Herbert 1993; Childs and Killick 1993; Mapunda 1995b; Schmidt 1997a, 2009; Haaland *et al*. 2002; Haaland *et al*. 2004; Haaland 2004a, 2004b; Killick 2007). To fully investigate the topics, the early researchers basically employed experimental, ethnographic, and oral historical methods, and in many cases they compared the results with those from other continents (*cf*. Childs and Schmidt 1985; Haaland 2004b; Anderson 2009). For the sake of clarity, the general results of the investigations of each of the topics are evaluated separately, in order to establish academic gaps.

To start with the first theme, although there have been numerous studies on the origin and spread of African ironworking, unfortunately we lack conclusive chronological

data. This is mostly because all Early Iron Age (EIA) dates are affected by the flattening of the radiocarbon curve in the mid-first millennium BC (Killick 2004a: 105). Because of the uncertain data, it has been difficult to conclude with precision whether or not iron technology in sub-Saharan Africa was an independent invention. There are some researchers however who have convincingly argued that hitherto there is no proof that iron smelting was introduced into Africa from anywhere else (e.g. Schmidt and Avery 1983, Holl 2009; Mapunda 2010). For instance, because the EIA technology of the Kagera region in north-western Tanzania and Taruga in northern Nigeria are so different from known European and Asian evidence, Schmidt and Avery (1983: 432) have suggested that they have an independent origin in Africa (see also Schmidt and Childs 1985; Craddock *et al*. 2007: 1). Some researchers think that we need new (dating) methods for further resolution on this theme (e.g. Killick *et al*. 1988; Killick 2008), but I strongly believe that the tyranny of origins will ultimately be difficult to prove on the basis of dates alone. Meanwhile, it is imperative to examine macro- and microscopic attributes of the archaeometallurgical remains, because this is as important as the dates, in order to improve our understanding of the variation of African iron and steel production.

Secondly, research on how iron and steel were produced in Africa has received relatively detailed attention. It is generally assumed that African ironworking was a bloomery process as opposed to the blast furnace process (e.g. Childs 1996). The end product of bloomery smelting was solid *soft* bloom (or iron), but the end product of the blast furnace process was liquid cast iron. Nonetheless, David *et al*. (1989) have published a different process in Mafa, northern Cameroon, thought to be in between the bloomery and blast furnace processes geared to produce *direct* carbon-rich steel with possible pockets of cast iron (for carbon-rich steel production elsewhere in northern and

western Tanzania, see Childs 1996; Schmidt 1997a; Mapunda 2010). On the basis of carbon-rich steel evidence, some archaeometallurgists think that probably iron technology in some African societies was more than a simple bloomery process (e.g. Childs 1996; Schmidt 1997a; Killick 2004a). Apart from that, Killick (2004a: 220) writes that "there is amazing variety of processes, many of which have no known counterparts on the other continents-a spectrum of variation of such diversity as to suggest that the term bloomery no longer does justice to the range of evidence". For example, in some societies in central and eastern Africa, iron technology was a three-stage process including bloom or iron refining in between smelting and smithing stages (e.g. Greig 1937; Chaplin 1961; Fagan 1962; Brock and Brock 1965; Maluma 1979; Davison and Mosley 1988; Barndon 2004; Mapunda 2010). For a better understanding of iron and steel production, it is imperative that such macroscopic variation of iron and steel production including the supposedly three stage process are fully investigated using chemical and mineralogical approaches.

Thirdly, the investigation on the symbolism and rituals of ironworking has relatively received more attention. It is well known that decorated iron smelting furnaces in some societies symbolised a woman ready to wed (e.g. Childs 1991; Collett 1993; Barndon 2004), or generally represented the human process of reproduction: adulthood, wedding, labour, and child-delivery (e.g. Wise 1958:109; Barndon 1996; Schmidt 1997a). It is also well understood that the rituals for iron and steel production served to expel evil spirits, catalyse the smelting process, and were used as a patent right of the smelters (e.g. Greig 1937; Wembah-Rashid 1969; van der Merwe and Avery 1987; Barndon 1996: 65; Craddock *et al*. 2007; Mapunda 2002a, 2010). While research on symbolism will probably continue, research on the ritual aspects is unlikely to continue productively, because almost all of the potential informants are gone (e.g. Killick

2004a; Barndon 2004; Haaland 2004a). It is however hoped that excavation of furnace remnants will potentially retrieve ritualistic items such as medicines in terms of either plant or animal parts, and pottery (see Mapunda 2010).

The over concentration on these three themes has unfortunately led to the neglect of other important aspects of African archaeometallurgy such as the extraordinary variation of iron and steel production in terms of its chemistry and mineralogy, how much iron was produced at the most important African iron and steel production sites, the history and technology of non-ferrous metallurgy in southern and central Africa, the role of water in African metallurgy (Mapunda 2010), and the bio-archaeometallurgy of African ironworking, which is the study of plant and animal species that were part and parcel of ironworking and their socio-cultural uses (Mapunda and Lyaya 2009; Lyaya 2011). In order to continue improving our understanding of African ironworking technology, it is essential that the neglected aspects receive due research attention, and that they are examined using archaeological material science methods. This thesis is one step towards that end.

1.3 Research Theme

Increasingly archaeometallurgists are becoming aware of the significance of macroscopic variation of iron production, and nowhere is this more obvious than on the African continent with its rich archaeological and ethnographic sources. Macroscopic variation of African iron production includes:

(1) technical ceramics such as furnaces, tuyère shapes, and pottery,

(2) furnace air supply mechanisms,

(3) iron technological stages (smelting, refining, and smithing),

(4) liquid slag handling techniques,

(5) final products of the three technological processes, and

(6) technological change or continuity of iron and steel production over time and space.

In order to improve our understanding of African metal production technologies, it is imperative that the macroscopic data are critically examined using microscopic techniques. To this end, some students of African metallurgy have studied the remains of metal production elsewhere (see Chirikure 2005; Humphris 2010; Iles 2011; Thondhlana 2012). Unfortunately, no one has examined if there is a systematic relationship between macro- and microscopic variation of iron and steel production. This thesis examines archaeometallurgical production remains in the southern highlands of Tanzania, with the view to explain the relationship between field (macroscopic) and laboratory (microscopic) data in the study of (African) metal production technologies.

1.4 Research Objectives

While the main objective is to examine the relationship between macro- and microscopic variation of iron and steel production in the southern highlands of Tanzania, specific objectives include:

(1) to examine the nature of the technical ceramics especially in terms of their refractory quality,

(2) to find out how iron and steel production furnaces were operated, especially in terms of air supply mechanisms,

(3) to investigate the presence of a three stage (smelting-refining-smithing) process of iron and steel (production) technology,

(4) to examine how (hot) liquid slag was handled during iron and steel production,

(5) to evaluate iron and steel reduction efficiency and its associated factors, and

(6) to discuss the nature of the final products of the smelting and refining processes.

1.5 Significance of the Study

This work is significant from different archaeological and archaeometallurgical perspectives.

This work expands the scope and improves our understanding of the archaeology of Tanzania, because the southern highlands of Tanzania have generally received less research attention compared to western, central, coastal, and northern parts of the country (for details on the trend of archaeological research in Tanzania, see Chapter 4 on study area justification). This work also is a useful future field guide for the identification and determination of the occurrences of archaeometallurgical remains in the southern highlands of Tanzania.

Archaeometallurgically, this study helps test oral and field (macroscopic) observation of the presence of the so-called iron refining process as opposed to the primary smithing process. It is demonstrated that the second refining or *vintengwe* process is clearly different from the first smelting or *malungu* process, both functionally and technologically. The former was geared to the production of carbon-rich steel, possibly with some sporadic pockets of cast iron, but the latter aimed at the production of soft iron. If the presence of this tradition is established elsewhere in central and eastern Africa, for example, I will be able to argue confidently that the iron and steel producers aimed at producing carbon-rich steel for good quality implements and weapons through the *vintengwe* technology (see also David *et al*. 1989; Killick 1991; Childs 1996; Ige and Rehren 2003). Since the production remains from the *malungu* and *vintengwe* processes are different from the third smithing stage, this work proposes that African iron and steel technology in some societies was a three stage process. This helps challenge the generally misleading understanding that all African ironworking processes

are simple variants of the bloomery process (see also Killick 2004a: 109; Schmidt and Avery 1978: 1085).

Lastly, this study demonstrates the potential of (chemical and mineralogical) slag studies to fully understand African iron metallurgy in terms of the end products, efficiency, and liquid slag handling techniques of the production processes. This study complements the use and over-reliance on smithing products such as (forged) iron tools alone (e.g. van der Merwe and Avery 1982; David *et al*. 1989; Kusimba *et al*. 1994; Miller 2001; Kusimba and Killick 2003) to discuss the nature of the end products of metal production processes. The usual low carbon content in the finished (forged) products (see Mapunda 2010) is far from representing the high carbon-rich steels produced by the smelting and refining furnaces. This study helps learn that some smelters and refiners in the southern highlands of Tanzania produced carbon-rich steels in the first (smelting) or second (refining) stage, and the high carbon steels were more likely (intentionally) decarburised to low or medium carbon tools during the third (forging) stage.

1.6 Definitions of Key Terms

As used in this work, the following key terms are defined. Note that the definitions of extra key terms are appended (see Appendix 1.1).

High carbon steel (production) refers to a carbon-rich (hard solid) steel produced in the smelting or refining furnace. It is indicated by wüstite-free slags and iron droplet inclusions in the slags.

Iron (production) refers to a carbon-free *soft* iron (also known as 'bloom') produced in the smelting furnace, with some impurities such as slag and charcoal (impure iron). Its production is indicated by the presence in the slag of some wüstite, irregular to angular iron particle inclusions, and an absolute absence of iron droplets.

Macroscopic variation refers to an array of physical attributes of the smelting and refining furnaces, tuyères, pottery, and the nature of the iron and steel production sites as observed in the field.

Malungu (or *ilungu* sing.) refers to the (later) large and tall (*circa* 3 m) *ore* smelting furnaces in Sumbawanga and Mbozi area districts. Note that this term is widely used beyond the borders of the two areas, in the Lake Nyasa-Tanganyika corridor region (*cf.* Phillipson 1968; van der Merwe and Avery 1987; Davison and Mosley 1988; Mapunda 2010).

Microscopic variation refers to differences in the chemical and mineralogical composition of the technical ceramics (furnaces, tuyères, and pottery) and the slags as determined using laboratory methods.

Vintengwe (or *kintengwe* sing.) refers to the small and short (*circa* 30-50 cm) *iron* refining furnaces in Sumbawanga and Mbozi area districts (they are distributed as the *malungu* above). In many cases, the *vintengwe* were situated next to the *malungu* furnaces.

1.7 Thesis Organization

This thesis is divided into eleven chapters:

(1) Introduction,

(2) Background: Physical Environment and Previous Understanding of the Archaeology of the Southern Highlands,

(3) Literature Review and Theoretical Framework,

(4) Applied Methodology: Rationale for the selection of the Research Area, Field, Experimental, and Laboratory Methods,

(5) Iron and High Carbon Steel Production in Sumbawanga,

(6) Iron and High Carbon Steel Production in Mbozi,

(7) Iron and High Carbon Steel Production in Mbinga,

(8) Iron Production in Iringa,

(9) Iron Production in Njombe,

(10) Discussion, and

(11) Conclusion.

Chapter two defines the research area in terms of the physical environment and the archaeology of the southern highlands of Tanzania. Chapter three critically reviews the previous knowledge in relation to the research problem, with more emphasis on the research objectives, in order to establish the gaps forming the need of this study. The other part provides the rationale for the adopted theories in this work. Chapter four discusses the methodology adopted in this work. It justifies the selection of the research area; provides the rationale for the selection of particular field, experimental, and lab methods and techniques to gather and analyse the data for this thesis. Chapters five through nine present and discuss new macroscopic and microscopic data from the research area districts including Sumbawanga, Mbozi, Mbinga, Rural Iringa, and Njombe respectively. Chapter ten discusses the specific research objectives of this work in relation to the new macro- and microscopic data of chapter five through nine. Chapter eleven is set to explain the research question or problem, based on the comparative discussion of the data in chapter ten. It is the last chapter, that also provides the recommendations and areas for future research.

1.8 Summary

This chapter has introduced the research topic and defined the research problem or question of this work. It has spelled out the overall and specific objectives, and most important of all, the significance of this work has been discussed. The key terms as used

in the whole thesis have been defined, and the layout of the thesis has been provided. The next chapter provides background on the research area.

2. Background: Physical Environment and Previous Understanding of the Archaeology of the Southern Highlands

2.1 Preamble

Part one of this chapter focuses on some aspects of the physical environment relevant for this work, in order to understand the relationship between the physical environment in terms of the resources for ironworking and the process of iron and steel production. Part two briefly examines the trend of previous archaeological research in Tanzania, and more specifically outlines what is generally known in terms of the culture and technology of iron and steel production in the research area. The purpose here is to justify the need for the current work in the area.

2.2 Part One: Physical Environment

This section examines the relationship between the physical environment and processes of iron and steel production in the southern highlands of Tanzania. The purpose is to reveal how positive or negative the environment was to the process of iron and steel production and vice versa. I dwell on a few but relevant aspects of the physical environment to the process of iron and steel production.

2.2.1 Geology and Mineralogy

Based on the most ancient rocks (Dodoman system), the geology of Tanzania is approximately 3700 million years (my) old (Schlüter 1997: 22). The other rock systems that occur in Tanzania and more importantly in the research area, based on the geological ages, include (1) the Ubendian Belt dating between 2050 and 1800 my

(Schlüter 1997: 60), (2) the Usagaran Belt (Schlüter 1997: 67), (3) sedimentary rocks of the Kibaran Belt or Karagwe-Ankolean rock systems dating between 1400 and 976 my (Schlüter 1997: 92), (4) the Bukoban rock systems dating between 1000 and 650 my and providing the earliest unquestionable fossil record in East Africa (Schlüter 1997: 95), (5) the Mozambique Belt rocks representing by far the longest zone of crystal mobility in the African continent and dating between 845 and 478 my (Schlüter 1997: 111), and (6) the Karoo dating between 285 and 187 my (Schlüter 1997: 143). For the purpose of clarity, the distribution of the rock systems in the research area districts is presented in Figure 2.1 below (see also Temple 1971a, 1971b; Schlüter 2006).

Figure 2.1: Geology of the Southern Highlands of Tanzania showing the rock systems. Note that the blank areas were not part of the research area (Modified from Temple 1971a).

The presence of iron ores is widespread throughout these formations and was critical for the production of iron and steel in the research area, because one cannot smelt iron without the iron ores as raw materials (*cf.* van der Merwe and Killick 1979). The rock

systems house iron-rich minerals such as magnetite, hematite, ilmenite, goethite, laterites, pyrite, and pyrrhotite (see Anthony *et al*. 1997), and when the primary rock systems undergo geological transformations they provide important resources in the form of, for example, black magnetic sands or limonite ores, for iron smelters.

2.2.2 Relief

The Southern Highlands is one of four upland zones in Tanzania. It is a line of high country extending from north of Lake Nyasa to the north of Morogoro (Berry 1971b: 26). In terms of relief, there is a great variation of the altitudes in this zone (Figure 2.2). The Southern Highlands generally rise above 1500 m (Berry 1971b), although there are a few areas with lower altitudes (Berry 1971a: 25). In order to present the variation in details, Figure 2.2 shows the distribution of the altitudes within and across the research area districts. It appears very much that iron and steel production activities in the region were patterned with the altitude as well: (1) the Fipa (Sumbawanga) and Nyiha (Mbozi) people worked in the plains (medium altitudes in the areas), (2) the Matengo (Mbinga) and Hehe (Iringa) people preferred to work in the mountains (high altitudes in the areas), and (3) the Bena (Njombe) people preferred to work in the river valleys (low altitudes in the area) (see village maps in Chapters 5-9). The variation in preferences of where they worked iron and steel could have been accidental, but it is known that smelting scenes were often carefully selected for technical and socio-cultural reasons (*cf*. Wembah-Rashid 1969; Sutton 1985; Lyaya 2012).

Figure 2.2: Relief of the research area districts. Note that the blank areas were not part of the research area (Modified from Berry 1971a).

2.2.3 Soils

Based on age, genetic features, and clay minerals, the soils of southern Tanzania can be divided into three categories, namely eluvial (leached soils occurring on well drained humid sites), illuvial (soils in which transported leached minerals or the direct products of rock decomposition in situ accumulate), and catenas (associations of soils, both eluvial and illuvial, in a repetitive sequence determined by relief and drainage) (Moore 1971b: 28). Each of the groups has been divided into sub-groups to reflect the nature of the clay mineral composition. First, eluvial soils are split into (1) skeletal, (2) skeletal to montmorillonoid, (3) montmorillonoid to kaolinoid, (4) kaolinoid brown soils, (5) kaolinoid red-earth soils, (6) sesquioxidic-kaolinoid, and (7) unweathered residuum or excessively sandy soils (Moore 1971b: 28). Second, the illuvial soils are split into (1) skeletal soils, (2) skeletal montmorilloid soils, (3) skeletal montmorilloid soils with

ironstone concretions, and (4) sesquioxidic-kaolinoid with a depositional horizon of massive ironstone (murram) (Moore 1971b: 28). Third and last, the catenas are split into (1) grey or black calcareous clays, (2) kaolinoid red-earth catena with a black calcareous lower member, intermediate soils have murram concretions, (3) calcareous bottom member dominant, (4) kaolinoid red-earth, calcareous bottomlands sequence, (5) kaolinoid red-earth, non-calcareous bottomlands sequence, and (6) sesquioxide catena (Moore 1971b: 29). The sub-groups have been used to classify the soils of the research area districts (Figure 2.3). For the purpose of agricultural activities, all the districts have fertile soils. This was important, because it is difficult to grow cash and food crops on infertile soils, unless iron tools were being produced for export alone. In addition, the soils of the research area districts were generally appropriate for the manufacturing of the technical ceramics (furnaces, tuyères, and pottery). It is difficult to believe that one would make tuyères and pottery from very sandy soils, without clay plasticity quality.

Figure 2.3: Soils of the Southern Highlands of Tanzania. Note that the blank areas were not part of the research area (Modified from Moore 1971b).

2.2.4 Vegetation

The vegetation of Tanzania has been the subject of careful investigation since even before independence (1961). Based on dominant life forms of plant associations (physiognomy), Keay (1959) classifies the vegetation of Tanzania into 12 life forms, although at a too low resolution (African vegetation) for complete accuracy (see Appendix 2.1). Because of the problem of the small scale not providing an acceptable degree of accuracy, Lind and Morrison (1974) relatively increased the resolution, from African vegetation to an East African vegetation focus. With this approach, they name nine vegetation life forms (see Appendix 2.2). The most accurate classification of the vegetation of Tanzania on a large scale is that by Moore (1971a: 30-31). It groups vegetation associations of Tanzania into (1) forest, (2) woodland, (3) bushland and thicket, (4) wooded grassland, (5) grassland, (6) swamp, and (7) desert and semi-desert. In this work, I adopt the latter scheme with some modifications to present the vegetation of the southern highlands of Tanzania (for details, *cf.* Figure 2.4). It is noteworthy that iron smelters often selected such special species (see Keay 1959; Lind and Morrison 1974; Moore 1971a) for technical and cultural purposes including wood for charcoal production, bellow accessories, rituals and medicines (e.g. Mapunda 2003a; Lyaya 2011). To elucidate, out of 28 tree species recorded in Uhehe (Mbuya *et al*. 1994: 18-19, see also Mathias 1982), only eight tree species were said to be selected by the Hehe iron smelters for charcoal production (Zuberi Waitala, 50 years old, interviewed on the 20th August 2011; see Appendix 2.3). The selection of tree and plant species for the process of iron and steel production does therefore not directly support some claims of total deforestation due to omnivorous consumption of wood by the smelters as advanced by Schmidt (1997b) and Stromquist *et al*. (1999). Rather, it is reasonable to posit that the relationship of vegetation and iron and steel production was a positive one.

Figure 2.4: Vegetation associations of the Southern Highlands of Tanzania. Note that the blank areas were not part of the research area (Modified from Moore 1971a).

2.2.5 Annual Rainfall

The Southern Highlands of Tanzania is one of the zones that receive high annual mean rainfall of over 1400 mm. Different districts of the research area receive uneven annual mean rainfall, from below 600 mm to above 1400 mm (Jackson 1971a: 37) (see Figure 2.5). As one might recognise, water is one of the key factors for domestic, social-economic, and technological development. For the case of archaeometallurgy, water was generally needed for the construction of furnaces, manufacturing of tuyères, medicinal and ritual performances, and for personal uses by smelters (see Mapunda 2010). In particular, the rainfall season (November-April) greatly influenced agricultural activities, and, conveniently smelting and refining activities more often took place during the dry season - July to October (Barndon 2004; Mapunda 2010; Lyaya 2011).

The seasonal variation of rainfall in Tanzania is partly influenced by south-easterly and north-easterly airstreams (Jackson 1971b). The lower layers of the former are fairly moist after crossing the southern Indian Ocean, but higher altitude conditions tend to be dry and stable (Jackson 1971b: 34). For the same reason, the north-east monsoon, originating from high pressure over Arabia and the north Sahara has a much more meridional track than the south-east airstream, moving either over a land surface, or at best, a short sea distance before reaching Tanzania (Jackson 1971b: 34). It is therefore drier than the south-east monsoon, and this, together with the fact that the airflow will tend to run parallel to the coast, greatly limits the rainfall.

Although there are three major lakes in the southern highlands of Tanzania including Lake Tanganyika, Nyasa, and Rukwa (see Berry 1971c: 32), it is possible that the smelters and refiners of the research area districts did not use water from the lakes, because they are relatively far from the smelting and refining sites. Instead, the metal producers used water of nearby site rivers, streams, and (natural) wells for the purposes of, among other things, furnace construction, and tuyère and pottery manufacturing (see Mapunda 2010; for details on distances of the sites to nearby water sources, see Chapters 5-9 and relevant appendices).

Figure 2.5: Annual mean rainfall distribution in the research area districts. Note that the blank areas were not part of the research area (Modified from Jackson 1971a).

2.3 Part Two: Previous Archaeological Knowledge

Here I examine what has been done in the research area archaeologically. The purpose is to justify the need of the current work in each of the five research area districts. Because there are different research trends in each of the districts, archaeological information in each district is discussed alone with its distinctive research objectives outlined, although at the end I list three common features of iron and steel production in the 5 districts.

2.3.1 Sumbawanga

Ufipa (Sumbawanga) is one of the areas in Tanzania that has received relatively more research attention especially in terms of the ethnography, anthropology, and archaeology of ironworking. The earliest writers on Ufipa ironworking, starting from the 1910s, were amateur ethnographers and anthropologists (e.g. Wychaert 1914; Greig

1937; Wise 1958), followed by professional ethnographers and anthropologists in the 1960s (e.g. Willis 1966, 1968; Wembah-Rashid 1969). These scholars largely focused on documenting iron smelting, refining, and smithing processes in Ufipa, based on interviews with retired smelters and observations of actual iron production processes, especially when the retired smelters were commissioned by British colonial administrators to demonstrate the processes. Next were ethnoarchaeologists and historical archaeologists between the 1970s and 2000s (e.g. Sutton 1985; Barndon 1992, 1996, 2004; Clark 1974; Mapunda 1995a, 1995b, 2003b, 2004, 2010, 2011). The latter scholars have written on the ethnoarchaeology, synchronic and diachronic variation, the social history, culture and socio-cultural implications of ironworking in Ufipa and its neighbourhood.

Based on metallurgical relics found in association with the Kalambo pottery tradition, which is related to Urewe ware in the interlacustrine region and the Mwabulambo and Gokomere traditions in Malawi and Zambia to the south, we know that between 400 and 1000 AD ironworking was already being practised (see Willis 1968; Clark 1974; Mapunda 2003b). The evidence from slags and tuyères indicates that the iron technology practised during this period was different from the *katukutu* and *malungu* techniques of the later groups (Mapunda 2004: 76). By 1000 AD, a variant of the triangular incised ware (TIW) pottery tradition seems to have emerged in Ufipa. Because TIW is largely seen as a coastal tradition, Mapunda (2003b, 2009) argues that it may have spread to Ufipa possibly through trade interaction between the coast and the interior (for similar view, see also Haaland 1993, 2005).

By 1400 AD, the *katukutu* ironworking technology emerged in Ufipa, as evident in the Nkansi district, northern Ufipa (Mapunda 1995a, 1995b, 2003b, 2004, 2010). This technology is characterised by relatively short furnaces, 80-120 cm high, globular in

shape, decorated with punched (dolly) holes using a stick or a finger, and operated by natural-draft air supply mechanism as indicated by the lack of flared tuyères (*cf.* Mapunda 1995a). Because *katukutu* sites are uniquely characterised by a paucity of metallurgical remains especially slags, Mapunda (1995a, 1995b, 2010) reasonably argues that this smelting technology possibly utilised high quality magnetite iron ores. The *katukutu* technology was followed by the *malungu* technology, which emerged around 1680 AD in southern Ufipa (Mapunda 2004), and reached south-western Tanzania around the mid-nineteenth century AD (Mapunda 2010: 159). Characteristic features of *malungu* include the use of limonite iron ores (Lyaya *et al*. 2012), and truncated and tall natural-draft furnaces ranging from 2.3-4 m high (Greig 1937; Wise 1958; Wembah-Rashid 1969; Mapunda 2010). Interestingly *malungu* furnaces are always located on the western side of a termite mound, most likely for cultural reasons (*cf*. Mapunda 2010), and had about ten tuyère ports, with multiple tuyères placed in each port horizontally but one on top of the other (Mapunda 1995a: 50). In addition, the *malungu* technology arguably has been associated with a separate iron (or bloom) refining technology in small forced-draft furnaces, called *vintengwe* (e.g. Mapunda 1995b: 50, 2003b: 76, 2010: 150; Barndon 1992, 1996, 2004). Because most if not all the smelted iron in the *malungu* was eventually refined in the *vintengwe*, the latter were often situated within several metres of the former (e.g. Wise 1958: 110; Mapunda 1995a: 50). Both the *malungu* and *vintengwe* were slag tapping processes (e.g. Greig 1937: 79; Wise 1958: 110; Mapunda 1995b: 50), although tuyères were used for this purpose with the former, and tunnels dug down slope were used to tap slag with the latter (*cf*. Greig 1937; Barndon 2004; Mapunda 2010). *Malungu* slag tapping through tuyères commenced when a pool of slag at the bottom of the furnace reached the level of the tuyères (*cf*. Mapunda 2010: 154). Before this, they all transmitted air into the

ilungu furnace. The question why the change of *katukutu* to *malungu* technology occurred has no easy answer. Mapunda (2010: 99) convincingly argues that the gradual shift from *katukutu* to *malungu* technology was due to a lack of magnetite ore in northern Ufipa for he writes, "as the magnetite ores became scarce, iron workers moved to the plateau [central Ufipa] where the low quality lateritic ore was plentiful. The change of ore quality compelled smelters to increase furnace size to accommodate big volumes of ore in order to gain a sizeable output". The other reason could have been a need to increase iron output, because *katukutu* furnaces were relatively less efficient compared to *malungu* furnaces (see Mapunda 2010: 176).

The *malungu* technology was followed by the Barongo-type forced-draft technology that emerged in the 19th century AD (Mapunda 2003, 2004). This technology is characterised by furnace slabs 60-90 cm high that were made from termite mound clay, and the furnaces had five tuyère ports, each for a single flared or trumpeted tuyères (Mapunda 1995b: 53).

In terms of the culture and symbolism of ironworking in Ufipa, a lot has been documented. Barndon (1992, 1996, 2004) discusses the cultural aspects of the *malungu* technology. She argues that the Fipa ironworking medicines, which were always securely kept in a special bag called *intangala* (e.g. Willis 1966: 24) and controlled by the master smelters, were important to help the smelt turn out successfully. According to oral evidence (Mapunda 2010, 2011), a successful reduction process was entirely a function of the smelting magic knowledge. Consequently, this trust made the chief smelters respected if not feared by people and automatically made them healers of people, especially during the rain seasons when smelting activities were often halted (Mapunda 2011). Symbolically, the (*malungu*) smelting furnaces were likened to brides, and the songs, ritual ceremony, and decorations resembled a wedding ceremony

(Barndon 1996: 69), while the (*vintengwe*) refining furnaces were modelled as women in delivery (Barndon 2004: 91). The use of magic, strong sexual taboos, and secrecy probably controlled the transmission of metalworking knowledge (Barndon 1996; for a similar view, see also Mapunda 2002a). Based on the culture and symbolism of the *malungu* and *vintengwe* furnaces, it has been argued that "it was the quality of the [carbon steels] produced in the secondary refining furnaces that determined the success of a [reduction process], and these had to be forgeable [steels]" (Barndon 2004: 91). Forging in open air hearths involved quenching, decarburization, and annealing techniques (Mapunda 2010: 186).

The socio-cultural significance of Fipa ironworking is well known. For example, Mapunda (2004: 78-83) interprets its socio-cultural context in terms of iron hoe symbolism, communal labour, political rank, protecting society, stratified economic well-being, and ironworking taboo promoting socio-cultural moral values. Mapunda (2004: 79-83) writes that (1) customarily an iron hoe was used to symbolise the passage to manhood and by extension a legal right to marry, (2) iron smelting stimulated communal labour and concentrated/ nucleated settlements, because settlements of this type were necessitated by the demand for communal labour for iron production, farming, and defence, (3) ironworking was an indicator of political rank, because smelting was an inherited skill and only members of designated clans could smelt and had the right to become leaders, (4) smelters were healers and protectors of the society, and (5) ironworking sexual taboos, for example, promoted socio-cultural moral values such as strengthening marital relations.

Although ironworking in Ufipa has received more research attention, there are several academic gaps that exist including: (1) while termite mounds were allegedly sources of clay for the construction and manufacturing of furnaces (*malungu* and *vintengwe*) and

tuyères respectively, no verification of the source and examination of the refractory quality of the technical ceramics has been done, (2) although Mapunda (2010: 154-155) outlines some physical features of slags differentiating smelting from refining process, no rigorous macroscopic and microscopic examination of the respective remains has been done hitherto, in order to differentiate the two processes, (3) no one has verified slag tapping practice metallographically as Mapunda (2010: 73) rightly observes, "although some scholars have classified [*malungu* and *vintengwe*] as slag tapping technologies e.g. Barndon 1992, no verification could be established by [themselves]" [added], (4) although Mapunda (2010: 174-6) compares efficiency of the *katukutu*, *malungu*, and Barongo-type processes, no one has examined and discussed the reduction efficiency of the *malungu* and *vintengwe* processes, and (5) there is a lack of clarity on the nature of the final products of the *malungu* and *vintengwe* processes, because Mapunda (2010: 186) thinks *vintengwe* produced carbon steel, while Barndon (2004: 91) links *vintengwe* with iron production, and yet Schmidt and Avery (1978: 1088) have argued that *malungu* could have produced steel. We need to find out also whether or not the production of iron or carbon steel was an intentional or unintentional practice.

2.3.2 Mbozi

The earliest ethnographic report on ironworking in Mbozi (Unyiha) was published in the 1960s (Brock and Brock 1965; Brock 1968). This work has recently been followed up by Lyaya (2010) and Ngonadi's (2010) work. While Ngonadi (2010) surveyed three wards: Isangu, Ihanda, and Igamba, all of which are located in the southern part of Mbozi, Lyaya (2010), as part of this doctoral project, has conducted ethnographic and surface surveys in Itaka and Kapele wards located in the northern part of the region.

One can see clearly that Mbozi is relatively and archaeologically *terra incognita*. Nevertheless, based on the three works, it has been hypothesized that the Nyiha, just like the Fipa (see Greig 1937; Wembah-Rashid 1969; Barndon 2004; Mapunda 2010), followed a three-stage ironworking process, involving ore *malungu* smelting, *vintengwe* iron (or 'bloom') refining, and iron smithing. Also, besides the *malungu* smelting furnaces, Ngonadi (2010: 56) presents archaeological evidences of globular smelting furnaces, morphologically similar to the *katukutu* furnaces of Ufipa, an older ore smelting tradition than the recent *malungu*, well documented from Ufipa (see Mapunda 1995a, 1995b, 2003b, 2004, 2010). Towards a better understanding of the ironworking process of Unyiha, our research aims at: (1) examining the nature of refractoriness of the technical ceramics, (2) investigating *malungu* and *vintengwe* furnaces air supply mechanism, (3) identifying liquid slag handling or collection techniques, (4) examining the nature of the reduction efficiency of the *malungu* and *vintengwe* furnaces, and (5) suggesting the nature of final products from the *malungu* and *vintengwe* furnaces.

2.3.3 Mbinga

Compared to Ufipa, this area has received relatively little archaeological attention. The only systematic archaeological investigation in northwestern (Lituhi) Mbinga was carried out in 1990 (see Mapunda and Burg 1991; Mapunda 1991, 2001). Based on these publications we know that the region was occupied by metal producers in the mid first millennium AD (Mapunda and Burg 1991: 35). While the exact shape of the iron smelting furnaces is unclear (Mapunda 2001: 108), it has been proposed that the furnaces of this area were forced draft ones with slag-pit provisions (Mapunda 1991: 69; Mapunda 2001: 107). Based on morphological and decorative motifs, the pottery of the region relates well to the Tana (or TIW) tradition (Mapunda and Burg 1991: 37; Mapunda 1991: 73, 2001; 109).

In addition, Kapinga (1990), an amateur archaeologist, has recorded ethnographic information from the sons and daughters of the former iron smelters in western (Litembo) Mbinga. According to the oral evidence, black (magnetite) sands from either rivers or along lake shores were used, and furnaces were about 1.5 m high, 1 m basal diameter, 15 cm top diameter, and were fitted with two opposite tuyère ports of which each housed four flared tuyères for bellowing (Kapinga 1990: 16). In addition to the four tuyères, a relatively short tuyère *kilokombi* used as a peep hole was placed in one of the ports (Kapinga 1990: 22). Unlike the northwestern part where the furnaces perhaps had slag-pit provisions, it is unclear from the oral evidence (e.g. Kapinga 1990) whether the furnaces of Litembo had a slag-pit as well, although Mapunda (1991: 69, 2001: 108) takes the view that iron technologies of the northwestern region and Litembo were similar irrespective of their spatial and temporal variation.

Besides the 1990 early archaeological research in northwestern Umatengo, no other archaeological or archaeometallurgical investigation has been carried out on metal production process in this area. The current research examines the macroscopic and microscopic data from northwestern (Ntuha sub-village) and eastern Umatengo (Kigonsera ward) in order to (1) find out the nature of the technical ceramics used to construct smelting furnaces, tuyères, and pottery for ironworking, (2) examine the archaeological evidence for draught mechanism for the smelting *matendi* furnaces, (3) verify whether or not recent iron smelting furnaces had slag-pit provisions (e.g. Mapunda 1991: 69, 2001: 108), (4) examine the efficiency of the metal production process, and (5) suggest the nature of the smelted metal products from the *matendi* furnaces of the two spatially and temporally different areas.

2.3.4 Rural Iringa

There is enormous historical data on the Hehe people of Iringa in part because they fought and allegedly defeated the Germans. Prior to the Germans, and under chief Munyigumba, the Hehe fought and defeated chiefs including Mtengela of Utemikwila, Merere of Usangu, and Chipeta of Ungoni, and won a decisive victory (Redmayne 1968b). In addition, under chief Mkwawa they respectively fought and defeated the Ngoni, Sangu, Maasai, and made brief raids in Unyanyembe, Ugogo, Usagara, and Uvidunda, all north of Iringa region (Mumford 1943; Redmayne 1968a, 1968b). They resisted the German colonial penetration into Uhehe, fought and defeated the Germans in 1891, but the Germans fought back in 1894, and ruled Uhehe in 1897. The Germans searched for chief Mkwawa for 18 months, but before they caught him, on the 19th July, 1898 Mkwawa committed suicide (?) at Pagawa (Redmayne 1968a). After the German war, the Hehe did not want to participate in any other wars including the Majimaji rebellion of 1905-1907 (Iliffe 1967). The enormous historical information on the Hehe was perhaps because the early writers wanted to justify colonial military intervention and administration in Uhehe (e.g. Monson 2000).

Archaeologically, the early research focused on the study of Isimila Stone Age site, and thematically, the research can generally be grouped into four parts: (1) the technology of the ESA (Early Stone Age) stone artefacts of Isimila (e.g. Howell 1961; Cole and Kleindienst 1974; Clark 1988), (2) the culture and environment of the hominids that lived at Isimila sites and its outskirts (e.g. Hansen and Keller 1971), (3) dating of the deposits of Isimila (Howell *et al*. 1962, Howell 1972; Clark 1988), and (4) the cultural sequences of the later prehistory of Isimila (Willoughby 2007; Kimaro 2008). Based on these studies, we know that Isimila site is largely composed of Upper Acheulian, MSA, and LSA artefacts (Willoughby 2007: 264-265), and dates to between 0.22 and 0.33

mya (Willoughby 2007: 265). Outside Isimila, there are Mlambalasi and Magubike rock shelters (all in Kalenga administrative division) with MSA and LSA occupations (Willoughby 2007; Biittner *et al*. 2007). The materials from the rock shelter sites have been studied macroscopically and microscopically with a view to understand the sourcing and variation of the raw materials and technology of the MSA and LSA people of the region (Biittner *et al*. 2007; Biittner 2011), and the origin and development of the use of points in hunting technology (Biittner *et al*. 2007; Bushozi 2011).

More importantly, there are lots of 'Iron Age' artefacts including slags, pottery, and grindstones in and around the rock shelters (Willoughby 2007: 265, 267; Biittner *et al*. 2007: 63, 64), but these have received no due weight in part because the previous researchers focused on Stone Age technology. Despite massive occurrences of archaeometallurgical remains almost everywhere in Kalenga, the only archaeometallurgical work carried out in this area was the author's MA fieldwork research in Mkoga (Kalenga) village (Lyaya 2007).

Besides the relatively good attention on historical and (mainstream) archaeological research, no one has specifically written on the technology of ironworking in rural Iringa. This is incorrect, because it has left Kalenga *terra incognita* archaeometallurgically. This project aims at rectifying this problem through: (1) exploring the nature of the technical ceramics, (2) finding out how the Hehe smelting furnaces were operated in terms of air supply mechanism, (3) investigating how the liquid smelting slag was handled during the iron smelting process, (4) examining iron production efficiency and its associated factors, and (5) suggesting the nature of the smelted product.

2.3.5 Njombe

There is a vast collection of historical information in Njombe including Bena (indigenous Bantu speaking tribe) history (e.g. Nyagava 1988, 1999), Bena pre and post-colonial political systems, migration, and administration (e.g. Swart 1964; Monson 2000), Bena bride-wealth system, and social cultural aspects (e.g. Culwick and Culwick 1934; Mumford 1943), and Bena and the Majimaji rebellion (1905-1907) (e.g. Iliffe 1967). Unfortunately, the archaeology of this area was utterly neglected in the German and British colonial periods. Post independence, Sutton (1985), Stromquist *et al*. (1999), Msemwa (2001), Halifan (2005), Lyaya (2007, 2008b, 2011), and Mapunda (2010) have sporadically and respectively written on the Bena iron smelting furnaces, Bena iron smelting and deforestation, ancient pottery and iron traditions in Njombe, Bena iron smelting symbolism, Bena iron smelting and smithing processes, and general chaîne opératoire of the Bena ironworking process. Unfortunately, all the previous studies have largely concentrated on the ethno-archaeology of the Bena ironworking, although two have looked at the archaeology of ironworking in this area (Msemwa 2001; Lyaya 2011). Besides this information, no one has examined the archaeometallurgy of the Bena ironworking. To this end, the research in this area specifically focuses on (1) examining the nature of the technical ceramics, (2) finding out how Bena smelting furnaces were operated in terms of air supply mechanism, (3) investigating how (hot) liquid slag was handled during the iron production process, (4) examining iron production efficiency and associated factors, and (5) discussing the nature of the final smelting product of the Bena iron production process.

The ethnographic data from the five districts point to several propositions. First, iron and steel production activities were intentionally secluded away from settlements in

bush or mountains, largely for socio-cultural reasons (elsewhere in Africa see Fagan 1962; Cooke 1966; Maluma 1979). For example, as elsewhere, in the Hehe society, pregnancy and child delivery are symbolically related to iron production process (see also Collett 1993; Schmidt 1997a, 2006; Mapunda 2010; Lyaya 2012). According to Hehe customs and traditions, an expectant mother (must) move away from her husband's house to live with her mother-in-law or with her own mother (Mumford 1943), where they are fully taken care of by renowned village midwives. Meanwhile, the husband was denied access to see the wife, mother(s), and midwives until the child was born and all the preliminary rituals successfully accomplished, a period that took up to two weeks. Although it is generally accepted that the (chief) iron smelters were symbolically the husbands of the (single) furnace wife (e.g. van der Merwe and Avery 1987; Herbert 2003; Schmidt 1997a, 2006), this conventional knowledge has three inherent problems: (a) an over-emphasis on polyandry culture in Africa, (b) it does not give due attention to a socio-cultural compulsory requirement of sex abstinence at the mature stage of the pregnancy, and (c) it silences the role of midwives and women in pregnancy and child delivery process, or rather in iron smelting symbolism. In order to rectify these problems, based on the Hehe iron smelting symbolism, (i) the real husbands who stayed home during a child delivery should symbolically be equated to women who were denied access to the iron production process, (ii) the midwives who were responsible for the child delivery process should symbolically be likened to the iron smelters whose responsibility was to ensure successful production of iron, and (iii) the pregnant woman would symbolically continue to be the smelting furnace and the bloom will be in place of the child. This symbolic interpretation of seclusion gives due weight to the role of midwives or women in iron and steel production symbolism and fits well in the context of the Hehe, Matengo (see Ndunguru 1972: 109-110), and Bena

(Mumford 1943). Seclusion was an advantage for the smelters got closer to the bulk smelting raw materials such as clays, ore, wood for charcoal as well as water (see Sutton 1985; Killick 1990; Mapunda 2010). The ethnographic data on Appendix 4.1 clearly indicate that ore sources, water, clay source, and wood for charcoal, in most cases, determined the location of the smelting and refining sites, because the archaeological sites are located to these materials. Botanical identification of the tree species and examination of potential ore source samples in relation to the slag chemistry remain an avenue for near future research (see Chapter 11, section 11.4).

Second, iron smelting (and refining) took place in the dry season, often between July and October (see Willis 1966: 23; Jackson 1971a; Basehart 1973). There was enough labour in this period (see Wembah-Rashid 1969: 69), because most people had finished harvesting and were mostly no longer involved in farming activities, which began in November or December with finger millet and maize cultivation (e.g. Willis 1966). It is difficult to understand why the smelters should have wanted to smelt in the rainy reasons, except in times of urgent needs such as fighting weapons for unforeseen (intertribal) wars, because inter-tribal wars were common in the research area during the late 19th and early 20th centuries (e.g. Redmayne 1968a).

Third and last, it strongly appears that ironworking activities in the research area were conducted on a large scale, because I have surveyed and systematically recovered a large amount of evidence for the ironworking tradition including smelting and refining debris and iron smithing sites in the villages (for a similar view elsewhere in Zimbabwe, see also Chirikure 2007: 84). There are several reasons for the need of a large scale production of iron and steel in the area including agriculture, marriage, and trade. For example, the Matengo whose recent history is relatively well documented (Basehart 1972; Ndunguru 1972; Halimoja 1977; Kapinga 1990), are famous for the cultivation of

coffee and tobacco as (major) cash crops and maize, beans, cassava, sunflower, and millet crops for food (Basehart 1973: 59). It is difficult to believe that this cultivation would have been achieved without the use of iron and steel tools such as hoes and bush knives for digging and tree clearing activities. In addition, iron hoes were traditionally required for dowry, in order for young men to get married (e.g. Mapunda 2004). Moreover, iron production in the research area was generally a source of wealth (see Kapinga 1990; Mapunda 2011). For example, twenty hoes could be exchanged for one cow, and one hoe bought one chicken (cockerel) (Kapinga 1990: 59). As well as the internal trade, allegedly the people of the eastern part of Lake Nyasa (including Mbinga), for example, crossed the lake to the western side of the lake (present day Malawi) to trade iron and pottery products for commodities such as ivory that were in high demand at the coast of east Africa (Mapunda 1991: 76, 2001: 108), to the extent that Davison and Mosley (1988) argue that this trade led to a decline of iron production in northern Malawi in the 18th century. Therefore, large scale and surplus production of iron and steel was required for agricultural activities, socio-cultural aspects such as dowries as well as for internal and international trade. This interpretation explains why it was difficult to outlaw iron smelting especially in Ufipa in favour of the imported foreign (colonial) manufactured iron tools in the early 20th century (Mapunda 2003a, 2004, 2010).

2.4 Summary

This chapter has made clear that there is a critical need to study the archaeometallurgy of the southern highlands of Tanzania, because the region has received less archaeological research compared to the other parts of the country, and that the research area has a good representation of the variation of iron and steel production techniques. It has also been shown that the physical environment of the area critically supported the

process of metal production in terms of essential iron ores for smelting, favourable clays for the furnaces, tuyères, and pottery, wood for charcoal and medicines, and conducive weather (and climate) for the smelting activities in the dry seasons. Lastly, it has been noted that mainstream archaeological research in the research area is clearly patchy, and no archaeometallurgical investigation has ever been carried out in the research area, excluding Ufipa (e.g. Mapunda 1995b, 2010), and hence the need of this study on macroscopic and microscopic variation of iron and steel production. The next chapter reviews the literature on this topic.

3. Literature Review and Theoretical Framework

3.1 Preamble

For the sake of clarity and in relation to the research objectives, the literature review section is divided into several parts including: work related to technical ceramics; furnace air supply mechanisms, *malungu* ore smelting and *vintengwe* iron refining processes; liquid slag handling techniques; iron reduction efficiency and ironworking final products. The purpose of the section is to identify academic gaps, demonstrating the need for this thesis. The theory section presents and justifies the adopted approaches in this thesis to explain the research problem. They include materials science, (2) social constructivist, chaîne opératoire, and symbolic and structuralist approaches. At the end a summary of the chapter is provided.

3.2 Literature Review

3.2.1 Technical Ceramics in Archaeometallurgy

The process of iron production involved the use of technical ceramics including furnaces, tuyères, and pottery as well as bellows for forced-draft furnaces. Rehren *et al*. (2007: 215) argue, among other things, that one needs a broad range of analysed materials, including technical ceramics and potential iron ores, and even fuel ash, in order to identify human choices that were part and parcel of the process. Because iron smelting and refining often reached high temperatures, the selection of clay for the construction of furnaces and the manufacturing of tuyères was an important aspect for successful smelts (e.g. Schmidt and Childs 1985: 91). In the words of Freestone and Tite (1986), selection of highly refractory ceramics suggests better skills and experience

of the smelters. Iron smelters and refiners often intentionally selected natural clays with good refractory quality to resist thermal shock (e.g. Killick 1990; Childs 1996). For example, Schmidt and Avery (1978: 1089), Schmidt and Childs (1985: 88) and Childs (1996: 309) write that the clays used to construct the preheating tuyères from both EIA and Later Iron Age (LIA) iron metallurgy in northwestern Tanzania were naturally refractory. The clays for the construction of EIA smelting furnaces in Rwanda and Burundi were naturally refractory as well (*cf*. Craddock *et al*. 2007). On the other hand, it is known that sometimes the smelters processed less refractory clays by tempering them, in order to enable them to survive high and fluctuating smelting temperatures (e.g. Schmidt and Childs 1985; Chirikure and Rehren 2004; Iles and Martinón-Torres 2009). To determine whether the technical ceramics were intentionally tempered to enhance their thermal properties, archaeometallurgists often rely on metallographic examination (e.g. Chirikure and Rehren 2004; Craddock *et al*. 2007; Iles and Martinón-Torres 2009). Artificial tempering is associated with the presence of angular temper minerals, especially quartz sands (Chirikure 2006: 148; Chirikure and Rehren 2006: 48), or the presence of both regular size and angular quartz (Iles and Martinón-Torres 2009: 2317). In the field, archaeologists use vitrification evidence of the ceramics to estimate the refractory quality of technical ceramics. Technical ceramics with good refractory quality show no or less vitrified ceramics or bloated tuyères (e.g. Childs 1996; Chirikure and Rehren 2004), and vice versa. Others more reliably use bulk chemical data to examine the refractory quality of the technical ceramics (e.g. Childs 1996; Chirikure and Rehren 2004, 2006; Craddock *et al*. 2007). It is generally accepted that refractory ceramics show relatively low levels of alkali metal oxides but elevated levels of aluminium oxide (e.g. Childs 1996; Chirikure and Rehren 2004, 2006; Craddock *et al*. 2007: 7). Technical ceramics with 3-4 wt% of potash would be less refractory

(Chirikure and Rehren 2004), but levels of between 26 and 30 wt% of alumina of the ceramic matrix excluding inclusions define good refractory tuyères (Iles and Martinón-Torres 2009: 2326). Here technical ceramics from the research area districts are chemically examined, in order to find out the source of the clays for all the technical ceramics, whether the iron smelters and refiners were clay selective for production of different technical purposes and the reasons for the selection of the clays.

3.2.2 Furnace Air Supply Mechanisms

Air supply raises the temperature in the furnace and is critically important for the reduction process (*cf*. Friede and Steel 1986a; Juleff 1996; Rehder 1999; Chirikure *et al*. 2009). Oxygen (O_2) combines with carbon in the form of charcoal to form CO_2, and further reaction of charcoal and CO_2 forms CO, a strongly reducing gas. For a better reduction effect, Killick and Gordon (1989: 120) have convincingly demonstrated that the ratio of CO/CO_2 has to be greater than 75%. In order to assess whether or not smelters (and refiners) reached such a ratio, it is important to first identify how the furnaces were operated. It is known that ore smelting (and iron refining) furnaces were bellows-driven or natural draft operations. Unfortunately, bellow remnants are difficult to recover in the archaeological record (*cf*. Chirikure *et al*. 2009), because of the decaying nature of the organic materials. Also, tuyère remnants are often too fragmentary or generally less informative of furnace air supply mechanism. Some scholars however associate the use of flared tuyères, whenever recovered in the archaeological record, with forced draft (smelting) furnaces (*cf*. Klapwijk 1986a; Childs 1996; Mapunda 2010), because the flared proximal ends served as receptacles for the bellows. Similarly, uniform diameter tuyères from tip to tip are thought to be indicative of natural draft (smelting) furnaces. Does the association of the shape of the proximal

ends and (smelting) furnace air supply mechanism work for the refining furnaces as well?

Yet, other scholars think that the height and size of the furnace and the number of tuyère ports per furnace can be informative of the furnace air supply mechanism (*cf*. van der Merwe and Avery 1987: 149; Holl 2009: 423; Humphris 2010: 40). Broadly, natural draft furnaces are relatively larger (1.5-3 m high) than forced draft furnaces (<1.5 m high) (*cf*. van der Merwe and Avery 1987). The former may have 5-10 (multiple) tuyère ports, and the latter may have 1-6 (single or multiple) tuyère ports (*cf*. Prendergast 1975; Sutton 1985; van der Merwe and Avery 1987; Haaland *et al*. 2002; Mapunda 2010), although some forced draft furnaces may have up to 15 (single) tuyère ports (*cf*. Haaland and Haaland 2000: 9-10; Haaland 2004: 71). By and large, it was supposedly difficult in terms of demand and arrangement of the bellowing labour if the forced draft furnaces had, perhaps, ten (multiple) tuyère ports each being operated by one man (sic) (*cf*. Cline 1937; Killick 1990; Chirikure *et al*. 2009). On this account, the smelters in southern Tanzania may have preferred fewer bellowers to operate a relatively small furnace. In contrast, it was convenient for the natural draft furnaces to have many tuyère ports, because the bellowing labour was not necessary. Unfortunately, this approach simplifies or ignores the fragmentary nature of archaeometallurgical remains, because rarely one would find still standing furnaces or furnace base remnants in the archaeological record. As such, archaeologists have often not given due attention to the study of furnace air supply mechanism. This thesis examines all macroscopic evidence chiefly related to furnace air supply mechanism, and investigates how such air supply mechanisms contributed to the efficiency of iron and steel production in the southern highlands of Tanzania.

3.2.3 *Malungu* Ore Smelting and *Vintengwe* Iron Refining Processes

Some archaeologists in Europe and Africa have established that the *direct* ironworking technology involved two stages, namely, iron smelting and (primary and secondary) iron smithing (e.g. Friede *et al*. 1982; Allen 1986; Rostoker and Bronson 1990; Greenfield and Miller 2004; Miller and Killick 2004; Chirikure 2006). Yet, others advocate a three-stage ironworking process involving iron refining between ore smelting and iron smithing processes (e.g. Greig 1937; Wise 1958; Wembah-Rashid 1969; Willis 1981; Barndon 2004; Lyaya 2009; Mapunda 1995b, 2010). Often, the typological studies especially of the slag relics from the two sets of ironworking processes lack clarity in this respect. The source of the confusion is the erroneous tendency to think that there may be a universally valid classification of the slags. To elucidate, the model of European *direct* iron metallurgy, which involved iron smelting and smithing processes alone, cannot fit and exactly describe some of the African ironworking processes, which we now know are greatly variable. Some societies in eastern and central Africa, for example, produced *direct* iron and steel through a three stage process including iron smelting, iron refining, and iron smithing. To support this with examples, when Allen (1986: 97) wrote that "we are here mainly concerned with the character of some of the slags known as smithing slags, which were formed during the *second* stage" he was correct from the context of European iron metallurgy. When Wembah-Rashid (1969:66) also wrote that "exactly there are three stages [in Ufipa, that is three types of iron slags]: the kiln [smelting], the blast furnace [refining], and the smithing [smithing]", he was also absolutely correct in the context of iron metallurgy in Ufipa. As such, smithing (primary and secondary smithing) process in European iron 'bloomery' metallurgy was *always* the *second* stage (see Allen 1986), but that was *not* always the case, for instance, in Tanzania, Malawi, and Zambia (e.g. Greig 1937;

Phillipson 1968; Davison and Mosley 1988; Killick 1990). Apparently there are some scholars working in Africa who have unfortunately been blindfolded by the European general assumption of classifying 'bloomery' slags only into smelting and smithing categories, ignoring the refining slags, although several African societies practised a three-stage process. To rectify this problem, it is imperative to document and examine properly the (field) macro- and (lab) microscopic attributes of the refining slags, in order to differentiate them from the smelting and smithing slags.

Hitherto the two-stage iron production process has been documented in Africa including southern Africa (e.g. Miller and Killick 2004; Chirikure 2006: 147; Chirikure and Rehren 2006), west Africa (e.g. Filipowiak 1985: 36), eastern Africa (e.g. Sutton 1985; Larick 1986; Childs 1996; Barndon 2004: 76; Craddock *et al.* 2007; Lyaya 2011), and central Africa (e.g. van Noten and Raymaekers 1988: 106). A separate iron refining tradition set between smelting and smithing stages is well documented in some societies in central and eastern Africa, including the Fipa and Nyiha of the southern highlands of Tanzania (e.g. Greig 1937; Brock and Brock 1965; Brock 1968; Willis 1966, 1968; Wembah-Rashid 1969; Barndon 1996, 2004; Mapunda 1995a, 1995b, 2004, 2010), the Tabwa of eastern Democratic Republic of Congo (DRC) (Mapunda 1995a), the Lungu and Kaonde of northern Zambia (Chaplin 1961: 54, 58), and the Phoka and Chewa of northern Malawi (Phillipson 1968: 102; Davison and Mosley 1988: 77; Killick 1990). There are also some publications indicative of the presence of the three stage process elsewhere in Zimbabwe (*cf.* Mapunda 2010: 159), southern Africa (*cf.* Stayt 1931, 1968), and Burkina Faso (*cf.* Timpoko 2003; Kiethéga 2009). The tall smelting furnaces in central and eastern Africa are linguistically more or less called *malungu*, and the small and short refining furnaces are called *vintengwe*. The term 'Tanganyika-Nyasa Corridor tradition' nomenclature also refers to the *malungu* and *vintengwe* traditions

(e.g. Davison and Mosley 1988; Barndon 1992, 1996), but this terminology does not stimulate the search for this technology elsewhere in Africa. I would suggest using more widely the terms *malungu* for ore smelting technology and *vintengwe* for iron refining technology, because they are geographically unlimited. In search of this often overlooked iron production tradition, this work focuses on the Fipa and Nyiha of southwestern Tanzania.

The *vintengwe* furnaces are almost cylindrical in shape, with a height ranging from 30 to 45 cm (Greig 1937; Wise 1958; Barndon 2004; Mapunda 2010), they had three draught holes, and were operated by bellows (e.g. Greig 1937; Brock and Brock 1965: 98; Phillipson 1968; Barndon 1996, 2004). In terms of spatial organization, the *vintengwe* furnaces in relation to *malungu* furnaces were located in three different ways: they were frequently situated next to *malungu* ore smelting furnaces for convenience, since the material to be refined in the *vintengwe* furnaces would be the iron or 'bloom' from the *malungu* smelting furnace (e.g. Davison and Mosley 1988: 77; Mapunda 1995b). They are located at a distance of between 15 and 37 m away from neighbouring smelting sites (Mapunda 2010; Lyaya *et al*. 2012). This meant that ore smelting was the first stage and 'bloom' refining was the second stage in the *chaîne opératoire* of ironworking in Ufipa and Unyiha. Greig (1937: 79) writes that "at the end of another day the kiln (the tall furnace) has burnt out, and after it has cooled the iron is sorted out from among the ashes. This iron still contains a great deal of impurity and has to be treated further in a miniature blast furnace". Secondly, in rare cases, early travellers, missionaries, administrators, and ethnographers observed that *vintengwe* furnaces were built near or in a village (*cf.* Greig 1937: 79), but Barndon (1996, 2004) claims that in Ufipa this stage was secluded from settlements. Thirdly, although the *vintengwe* furnaces would have been secluded from the settlements, it does not mean that they

were always situated next to *malungu* furnaces; they were sometimes located away from the smelting in a separate iron refining industrial area (Lyaya 2009; Lyaya *et al*. 2012). The seclusion of iron refining (and smelting activities) can be related to the popular child-delivery-iron symbolism and to ritualistic reasons. Regardless of where the *vintengwe* furnaces would be located, it is vital to note that they were *always* located on a sloping ground, in order to facilitate the slag tapping (*cf.* Wise 1958: 110).

In terms of rituals, Davison and Mosley (1988) note that no taboos were attached to the secondary iron refining process. However, Barndon (1996) argues that the Fipa *vintengwe* furnaces did have the anthropomorphic attributes of a woman, and that medicinal barks from different tree species and animal bones as well as a 'white juice' were used as part of the rituals. The taboos surrounding the refining process may have been in place together with those related to the smelting process, and performed especially during the construction stage of the furnaces. For example, Brock and Brock (1965: 100) write that "as he [the master smelter] prayed to *mulungu* (Nyiha divinity) cocks were killed and their blood spread on the large (*ilungu*, sing.) and small (*ishitengwi*, sing.) furnaces".

It is generally understood that the technological function of this second stage in the eastern and central African iron production *chaîne opératoire* (Barndon 2004: 92) was to improve the quality of the 'bloom' from the *malungu* furnaces, in order to produce quality tools and weapons (*cf.* Wise 1958: 111; Willis 1966: 25; Davison and Mosley 1988: 77). Although Killick (1990) and Barndon (2004) have generally proposed that the *malungu* process did not always produce forgeable iron or 'bloom', Wise (1958) convincingly argued that the *malungu* furnaces produced forgeable axes and hoes for women (sic), while the *vintengwe* furnaces produced forgeable axes and hoes for men (sic). What remains unclear, however, is the nature of the material at the end of the

refining stage: did it produce soft iron, or carbon-rich steel? This thesis examines the efficiency of the process, and identifies the end product of the *vintengwe* furnaces.

3.2.4 Liquid Slag Handling Techniques

In the process of metal production, the liquid slag has to separate from the metal itself. Because the slag accumulates and finally fills the furnaces, it has to be drained elsewhere either inside or outside the furnace. It is generally understood there were two fundamental techniques to handle the liquid slag: the slag-pit provision, where molten slag drained to the bottom of the furnaces in special pits (e.g. Schmidt and Avery 1978, 1983; Friede and Steel 1985; Celis 1987; Childs 1996), and the slag tapping, where most slag was allowed to flow out of the furnace (e.g. Wise 1958; Phillipson 1964; Barndon 2004; Mapunda 1995a, 1995b, 2010). There is a general assumption that the slag-pit provision method was common in the EIA furnaces, while the slag tapping process was popular in some locations in LIA furnaces (e.g. Schmidt and Avery 1983: 431; Schmidt 1988: 36; Schmidt and Childs 1985: 56; Mapunda 2002b: 78). For example, based on furnace evidence as well as slag, Craddock *et al*. (2007: 4) write that the EIA Urewe furnaces in Rwanda and Burundi had slag-pit provisions (for a similar view elsewhere in Ethiopia and Mauritania, see Haaland *et al*. 2002: 38; MacDonald *et al*. 2009: 37 respectively). This generally accepted thinking has however one intrinsic problem; it simplifies the reconstruction of the early and later liquid slag handling techniques, which are complicated and far from such simplistic explanations (see Haaland and Msuya 2000). In addition, the model does not work universally, because there are non-slag-tapping furnaces in the later prehistory of African iron metallurgy (see Childs 1996: 285), and there are tall furnaces in the Sahel, which had slag-pit provisions (see Killick 1991: 63). Furthermore, the association of natural draft furnaces with slag-tapping technology does not do justice to tall and short furnaces such as those

of the Matengo (150 cm high) in southern Tanzania (see Kapinga 1990), or those from Swart and Baranda villages in northern Zimbabwe (see Chirikure and Rehren 2006), which were bellows-driven and slag tapping furnaces. All this reflects the great variation of African ironworking technology, where generalisation would rarely work. There is a need to work consciously with the assumptions, and give due attention to field and lab examination of the archaeometallurgical relics themselves.

In the field, tap slag can be differentiated from furnace slag through several attributes. First, one of the quickest but sometimes misleading attribute is the flow texture of slag. For instance, Haaland (1993, 1994/1995) used this attribute (including the massive tuyères) to propose a slag-tapping technique at the Dakawa EIA site in Tanzania, but later on she challenged her earlier interpretation and turned to suggest a non-slag-tapping technology (Haaland and Msuya 2000; Haaland 2005). The problem with flow slags, they argue, is that it can be produced by non-slag tapping furnaces as well (Haaland and Msuya 2000: 81), which is true and consistent with findings from Uhaya (*cf.* Schmidt and Childs 1985: 56), and Uhehe (*cf.* Lyaya 2007). Second and in addition to flow slag, they recovered what is thought to be slag-pits, impressed slags with wood, and the examination of one tuyère showed no internally oxidized tuyères (Haaland and Msuya 2000: 82). Internally oxidized tuyères have been associated with slag-tapping (e.g. Chirikure and Rehren 2006: 50), although there are some no internally oxidised tuyères at the *malungu* ore smelting sites in Ufipa and Unyiha (see Mapunda 2010: 154). Although impressed slag can be used to strengthen the slag-pit explanation, it is worth noting that archaeologists in the field have encountered slag with wood impressions from slag-tapping furnaces (Mapunda 2010). But this happens rarely and it can be attributed to the wood and logs that were laid first at the bottom of the furnace before charcoal and ore were charged on top respectively (*cf.* Kapinga 1990; Barndon

2004). The study by Randi Haaland at Dakawa, east central Tanzania, is an example of the complicated process of the reconstruction of how the slag and metal were produced. Third, if the researchers at Dakawa, for instance, had additional evidence including tuyère mould slags (e.g. Chirikure and Rehren 2006: 50; Mapunda 2010: 155), their initial interpretation would have been sustainable. This type of slag morphology is exclusively characteristic of the slag-tapping process. Nonetheless, it should be noted that slag tapping at Lopanzo in Equateur province of DRC was done through a slit or tunnel (Ackerman and Killick 1999: 1135). That is more or less similar to the way slag was tapped from the *vintengwe* furnaces in Ufipa (e.g. Wise 1958). Thus, we should not necessarily expect tuyère mould slags at such sites. Lastly, Randi Haaland's second interpretation of the slag-pit method at Dakawa unfortunately lacks sufficient evidence of droplet slag, which is an important characteristic of slag-pit furnaces, as Schmidt and Childs (1985: 56) put it, that "smelting droplet slag form as slag drips down through the slag matrix, when cooled, they sometimes may be observed as larger lumps of slag that are flat on the bottom, glassy looking, smooth, and dense. Small beads (3-6 mm) and larger twisted prills are found on the floor of the furnace and are, therefore, excellent diagnostic markers for smelting when found in an archaeological context, particularly on the floor of a suspected furnace pit". However, it is noteworthy that there are droplet slag from smithing sites too (e.g. Miller and Killick 2004; Lyaya 2007), but the droplets from smithing sites are often hollow and were formed during the primary smithing of the 'bloom' (e.g. Miller and Killick 2004). To sum up, in the field one needs to cross-cut all this evidence to test the hypothesis for liquid slag handling methods, but this is unlikely to be simple and straight forward in the field. Since it is difficult to provide a conclusive explanation based on the field evidence alone, it is important to include laboratory methods, which are likely to provide proofs for our hypothesis, or as Childs

(1996: 315) puts it, "laboratory studies provide glimpses into the traditions and innovations that ironworkers have developed within specific cultural and environmental contexts. They provide a corpus of data that can be compared and used to study and explain the variation that once existed in ironworking techniques around Africa and the world".

In the laboratory, archaeometallurgists are able to differentiate tapped slags from non-tapped slags, or furnace slags. The microstructures of tapped slag are quite different from those of the furnace slags, because the two sets of slag cooled at distinctively different rates. Tap slag is associated with rapid cooling under disequilibrium, and the fayalite phase would be dendritic and elongated because the crystal structures had not enough time to grow to their original and normal structures (e.g. Ige and Rehren 2003; Chirikure and Rehren 2006; Humphris *et al*. 2009; Lyaya *et al*. 2012). Conversely, a blocky microstructure of the silicate phase would directly indicate that the slag slowly cooled possibly at nearly equilibrium conditions in the furnace (e.g. Chirikure and Rehren 2006). Under normal circumstances, the former will comprise more of the glass phase and fluxing alkali and earth alkali metal oxides, but the latter constitute less of these and possibly more of aluminium oxides including other metal oxides which melt at high temperatures (e.g. Chirikure 2006).

Furthermore, tap lines or magnetite skins can be used to differentiate tap slag from furnace slag (*cf*. Chirikure 2006; Lyaya *et al*. 2012). The formation of magnetite skins is related to contact of the flowing slag with an ambient air that oxidizes its surface to form the magnetite skins before it cools out or another slag tapping episode comes on top of it. However, depending on how the sample was selected and prepared in the laboratory, the magnetite skins may not be revealed during microscopy examination. Noteworthy is the fact that even furnace slags could sometimes be exposed to more

oxidizing conditions, say in front of the tuyères, or accidentally exposed to oxidizing conditions during 'bloom' removal, all of which may quickly form magnetite skins. If this happens, it is possible to tell the difference by examining the microstructures of the slag phases and the present phases, from which we will be able to tell the process that produced the respective slags.

In sum, the problem of similar flow textures in both tapped and flown furnace slag would be resolved by microscopic observations. This thesis uses both field and laboratory evidence, in order to identify how the liquid slag was handled during iron and steel production processes in the southern highlands of Tanzania.

3.2.5 The Efficiency of Ironworking Technology

The Oxford Advanced Learner's Dictionary defined efficiency as the relationship between the amount of energy that goes into a machine or technological process and the amount that it produces (Hornby 2005: 489). Efficiency as applied in this work involves the skills and experience of the smelters and refiners to optimally adjust the smelting and refining parameters required to systematically produce desired products (iron, or steel) in relation to the nature of raw materials (ore, or clay), labour, fuel, and time factors. This definition groups efficiency into labour efficiency, fuel efficiency, time efficiency, and ore (technical) efficiency.

Some of the early writers on African metal production technology envisaged the durability of the iron tools (e.g. hoes) produced as a measure of efficiency. Comparing the Fipa iron hoes and the industrial iron hoes, Wise (1958: 111) wrote that the former were more efficient than the latter, because the former lasted the owner four cultivating seasons that is at least twice as long as the factory made hoes. Sutton (1985: 175) also claims that the efficiency of two iron producing societies can be determined by measuring how much iron metal was produced per single smelt by the respective

societies. There are practical problems with these two approaches. To start with the tool approach, it is known that use and weathering of the iron tools left only small parts that are less informative of the primary technology and almost impossible to provenance. With the other approach, it is practically difficult to access information on iron metal quantities produced in early and later iron production processes.

Alternatively, the third and perhaps most popular is the slag approach. Because the principal and technical goal of iron smelters was to reduce iron from the iron ore, one of the tasks of archaeometallurgists has been to find out the level of success of the smelters. The other task is to establish the responsible factors for the achievements or failures of the smelters. Often there is an agreement that the less free iron oxides are in a slag, the more technically efficient were the ironworkers, and vice versa (e.g. Morton and Wingrove 1969, 1972; Bachmann 1982; Killick 1991; Childs 1996; Ige and Rehren 2003; Miller and Killick 2004; Chirikure and Rehren 2004, 2006; Mapunda 2010). It is noteworthy that concentration on good slags is important but by itself is not enough, because it ignores the factors that contributed to the production of such good slags.

There are several factors to technical efficiency. *First*, the nature of the smelted iron ores in terms of purity and chemical composition affected the iron smelting technology and the type and quality of the resultant iron and slag chemically and mineralogically. In terms of purity, either very pure or very impure iron ores are not good to smelt. It is inadvisable to smelt a very poor iron ore, because the gains will be almost negligible. In fact, it is impossible to reduce iron from very poor iron ores, because the total iron oxide would be insufficient to form slag with the amount of silica and alumina present (Morton and Wingrove 1972). Although with difficulty, smelters in Kasungu in Malawi smelted iron from poor grade ores (see Killick 1990). Iron smelters improved the ferrous content of low grade iron ores by the beneficiation process (e.g. Kapinga 1990;

Childs 1996). On the other hand, very rich iron ores are difficult to produce technically efficient slags, because we must have large iron losses into the slags, and the product would be low-carbon iron (Tylecote *et al*. 1971: 352). In general terms and keeping other factors constant, it can be thought that iron ores with medium ferrous content (60-80%) could produce good slag, but in practice probably this was not always the case. While others were lucky and smelted self-fluxing iron ores, ironworkers with very rich iron ores may have added some fluxes into the furnace, possibly to allow the formation of low-iron slags (e.g. Whiteman and Okafor 2003; Rehren *et al*. 2007). For example, the technical efficiency of iron smelting slags of the Njanja people in Zimbabwe was related to the use of sand as flux to the high grade haematite ore with about 80% ferrous content (e.g. Chirikure 2006: 149). Also, one of the factors for the medieval 'bloomery' process efficiency was due to the addition of limestone as a flux (*cf*. Morton and Wingrove 1972: 478). The issue of relating intentional addition of sand or quartz into the furnace and technical efficiency is complicated, but it is possible to find out whether the efficiency could have been due to other factors as well. According to Ige and Rehren (2003: 20), the formation of ulvite crystals due to the introduction of ilmenite, rather than fayalite due to sand as flux, was beneficial for the efficiency of the process of iron smelting at Modakeke, western Nigeria. This is because each silicon atom of silica requires two atoms of iron to form fayalite, but each titanium atom of titania needs one iron atom in ilmenite to form ulvite, which relatively lets less iron oxide go into the slag. But it is necessary to mention that it is possible to produce an efficient slag from smelting a low grade iron ore, which was not blended with another titanium rich iron ore. According to Iles and Martinón-Torres (2009: 2323), the efficiency of iron smelting at Mili Sita on the Laikipia plateau of Kenya was due to, among other factors, enrichment of lime and manganese oxides, because these will combine with silica in the

olivine, which frees more iron oxide to reduce to metal and leaves relatively little iron oxide in the slag.

Second, the size and volume of the iron ore pieces charged into the furnace was critical to the efficient production of good slag, because neither too big iron ore particles nor too small iron ore pieces would have enhanced the reduction process. One practical explanation is that too big pieces would have taken long time to smelt, and too small pieces, including dust, would have easily suffocated the fire in the furnace and the whole process could have halted (e.g. van Noten and Raymaekers 1988; Childs 1996; Whiteman and Okafor 2003). Therefore, the optimal size controlled the ore so it did not fall rapidly through the stack, in order to allow sufficient time for the reaction process (e.g. Childs 1996). Ironworkers possibly through repeated experience got to know the optimal size of the ore pieces to smelt. The Madi ironworkers of Democratic Republic of Congo (DRC) roasted their haematite ore to make it brittle and easier to break into appropriate size for efficacious smelting, and prior to smelting they sieved out the dust (van Noten and Raymaekers 1988: 106). In Modakeke, south-western Nigeria, the dirt was removed through washing in streams after which the ore nodules were dried prior to smelting (Ige and Rehren 2003). The size of the ore pieces varied across societies: from pea and nut-sized grains in northern Malawi (Davison and Mosley 1988: 67), or walnut size in Kaonde ironworking (e.g. Chaplin 1961) to coarse sand or gravel size at Modakeke iron smelting site (e.g. Ige and Rehren 2003), and more precisely in both pre and colonial ironworking among the Haya in south-western Tanzania the size of the broken ore pieces was 2 cm^3 (Childs 1996: 285).

Third, the furnace height and structure might have been responsible for efficient production of good quality iron metal, because a long reduction zone measured by either the stack itself or together with the furnace pit was critical (e.g. Childs 1996; Killick

2004a). According to Childs (1996), the structure of the furnace determined the efficiency of Haya iron smelting, because the combination of the stack and the slag pit height provided a fairly long approximately 2 m reduction zone. In addition, the furnace-pits initially filled with grasses or reeds and later with charred fuel provided a structure which kept the charge elevated in the stack (Childs 1996: 285-295). Also, according to Whiteman and Okafor (2003), the importance of bed-depth was to provide an indirect reduction that eventually controlled the technical efficiency of bloomery furnace operations. Noteworthy is that not all iron furnaces had slag-pits and that there are taller furnaces than Haya furnaces which had no slag-pits (e.g. Grieg 1937; Mapunda 1995a; Barndon 1996; Chaplin 1961; Davison and Mosley 1988). So it can be argued that it is the overall height of the stack, which is related to the length of time that the ore has to be reduced to metal in the furnace stack before slagging commences, which matters. Some writers have claimed that the long slow combustion in tall natural or forced draft furnaces possibly contributed to the production of steel 'blooms' (Childs 1996; Ige and Rehren 2003; Killick 1991, 2004a), but this needs metallographic confirmation.

Fourth is the fuel to ore ratio. It is known that iron smelting furnaces were charged with ore and charcoal, but more important and interesting was the question of how much of each was charged and smelted together into the furnace, with the view to produce good quality iron metal. The principle is that low fuel to ore ratio is fuel efficient but technically inefficient, because increased fuel consumption is needed in order to remove more iron oxide from the system as metal (e.g. Rehren *et al*. 2007), and vice versa. In this context and as noted earlier, reducing the efficiency of ironworking to technical efficiency is an incomprehensive approach, because fuel efficiency is equally and critically important. The fuel to ore ratio controls the chemical composition of the iron

and slag fluidity (e.g. Whiteman and Okafor 2003), because chemical constituents of fuel ash, including phosphate, potash, lime, soda, and magnesia lower the melting temperature of the slag, which is beneficial for the formation of both good iron and slag (e.g. Childs 1996). According to Wise (1958: 109), the *malungu* furnaces of the Fipa, southwestern Tanzania, were charged with 53 basketful of charcoal and 70 basketful of iron ore, which is equivalent to a ratio of 1 to 1.3 by volume, but the Orba iron smelters at Modakeke, southwestern Nigeria, charged their furnaces with fuel and ore at a ratio of 10 to 8, which was technically efficient on the expense of fuel and possibly led to production of steel for good quality implements and weapons (Ige and Rehren 2003). Iron smelters at Kasungu in Malawi liked the ratio of 19:1, which similarly may have facilitated possible production of steel, because metallographic analysis showed they produced lean slag composed of skeletal fayalite and glass with little or no wustite (Killick 1991). The ratio of 19 to 1 is wasteful and clearly fuel and possibly labour inefficient, but judged from the leanness of the slag, this was a technically efficient iron smelting process. Therefore, there are always various costs associated with the production of good slag, which should be given due attention while discussing the efficiency of African ironworking (e.g. Rehren *et al*. 2007).

Lastly, the control of air supply during ironworking affected the technical efficiency of ironworking, because a constant and sufficient supply of air is needed into the furnace to form carbon monoxide (CO), which in turn is needed to reduce iron from the ore. Ironworkers by means of experience met this condition by introducing the use of multiple tuyères and bellows to ensure they reached their desired goal. The Medieval 'bloomery' furnaces were made efficient by the use of water-powered bellows (e.g. Morton and Wingrove 1972: 478), and the use of furnaces with multiple tuyères and bellows was critical to a technically efficient ironworking process by the Njanja of

Zimbabwe (e.g. Chirikure 2006). Also, according to Humphris *et al*. (2009), iron production at Birinzi in Uganda was standard and technically efficient, because ironworkers constantly and effectively controlled the engineering factors especially air supply throughout the smelting process, which did not transpire at another site Kinanisi, a technically inefficient iron smelting site. But it should be noted that the local variations between two or more iron smelting sites in terms of technical efficiency can be explained in relation to knowledge transmission of the technology (e.g. Craddock *et al*. 2007; Humphris *et al*. 2009). The technology of pre-heating has also been associated with the production of steel 'blooms' in Uhaya. According to the proponents of the practise, between 36 and 50 cm of the tuyères were inserted inside the furnace, which facilitated the preheating of the air to about 600 ^{o}C before it was released into the furnace, and this situation eventually led to the production of massive steel (Schmidt and Avery 1978, 1983; Childs 1996). The Haya slags contained very little wustite possibly because of the pre-heating technology which reached smelting temperatures to between 1300 and 1400 ^{o}C and more (e.g. Schmidt and Avery 1983; Childs 1996), but this reconstruction of an advanced and prehistoric ironworking technology in Uhaya has been criticised and reassessed respectively (e.g. Rehder 1996; Killick 1996).

In sum, it is necessary to point out that there are different colours of the term efficiency, which should be discussed in their totality when examining the efficiency of iron and steel production technology. We should not be misled by mechanical engineers' definitions of efficiency: we are archaeologists and our role is clear, study both field and laboratory cultural evidence to fully understand human culture.

3.2.6 End Products of Iron Metallurgical Process

The process of metal production in Africa involved two (smelting and smithing) or three (smelting, refining, and smithing) stages, depending on which part of the continent one

refers to. It is reasonable to think each of the stages must have produced different products. Unfortunately, there is over-reliance on the nature of the smithing stage products via the study of finished tools such as hoes, knives, and axes (e.g. van der Merwe 1980; van der Merwe and Avery 1982; Mapunda 2010). Sporadically, it has been found that the forged tools were (low) carbon steels (see van der Merwe 1980; van der Merwe and Avery 1982; Kusimba *et al*. 1994; Kusimba and Killick 2003; Mapunda 2010). Ironically, some Eurocentric scholars have dismissed claims of (smithing) carbon steels in Africa saying that they were accidental production (e.g. Cline 1937). One problem of the use of iron artefacts is that they are less durable in the archaeological record, because iron-rich material easily reacts with H_2O and O_2 to eat and rust the metal quickly. The other problem is that the amount of carbon in the (smithing) tool is likely not to represent the amount of carbon in the smelting or refining product. Another approach has been the study of the smelted (and refined) products (e.g. David *et al*. 1989; Childs 1996; Barndon 2004; Schmidt 1997b, 2006). But the (*real*) smelted (and refined) products are often not available for us in the archaeological record to study. Because of these problems of both the artefact and smelted product approaches, it is imperative to resort to the study of the production remains (e.g. slags) of the (smelting and refining) processes, in order to understand the nature of the smelted and refined products. This thesis examines slag remains, with a view to explain the nature of the smelting and refining products in the southern highlands of Tanzania. This helps to understand the technological and functional significance of the refining process in Ufipa and Unyiha.

3.3 Theoretical Framework

Explanation in science is constantly changing (see Kuhn 1970, 1996), because of the desire to develop better scientific explanation (*cf*. Gibbon 1989, 2005), and archaeology

is no exception. In archaeology, explanations of the human past include processual (1960s), post-processual (1970s), and cognitive-processual (1980s-1990s) paradigms (see Renfrew and Bahn 2012 Chapter 12). There may be different theories in a paradigm, depending on certain internal criticisms or disagreements, although they should be similar in many cases (*cf*. Guba and Lincoln 2005: 191-216). Selection of one paradigm or the other, among other factors, depends on the nature of the data under question (*cf*. Gibbon 1989: 144), the temporal scope of the data (*cf*. Killick 2004b: 575), and the nature of the research question. As Renfrew and Bahn (2012: 470) rightly put it, "different things require different kinds of explanation". This work on African iron and steel production basically deals with actual or observable archaeological data (e.g. slags, furnaces, tuyères, and pottery) and, in a way, unobservable cultural phenomena (e.g. ideas, beliefs, symbolism, and ideology). The latter non-empirical dimension was improbably responsible for the structure and production of the former empirical dimension, and hence, for a comprehensive explanation of the African metal technology, it is imperative not to overlook the social context of iron technology (*cf*. Killick 1990; Pfaffenberger 1992; Reid and MacLean 1995; Schmidt 1996, 2009; Barndon 2004; Mapunda 2010). As will be clear below, I have employed materials science approaches to explain the properties of the archaeological materials in relation to technological choices (e.g. Sillar and Tite 2000; Jones 2004), and realist approaches including social constructivist/ constructionist, chaîne opératoire, and symbolic and structuralist theories to explain the dispositional factors of the smelters and refiners.

3.3.1 Materials Science Approaches

Materials science studies the properties of archaeological materials, in order to improve our understanding of the human past (e.g. Childs 1996). There is a common consensus that scientific examination of the archaeological materials is a necessary stage in

scientific archaeological inquiry (*cf*. Childs 1996; Sillar and Tite 2000; Jones 2004). One major contribution of materials science is that it provides a methodology and physical and chemical characteristics of the materials for the study of technological choices (Sillar and Tite 2000: 17). We are able to explain questions such as why the artisans selected one of the manufacturing techniques of copper, and not others (*cf*. Lechtman 1977: 7), or why iron smelters selected kaolin clay alone for the manufacturing of the tuyères (*cf*. Childs 1989a, 1989b, 1990). Also, one can use this approach to examine whether iron and steel (reduction) processes were efficient (*cf*. Humphris *et al*. 2009; Iles and Martinón-Torres 2009). Lastly and in particular to this work, this approach has been used to explain the nature of the final products of the smelting and refining processes in the region (see Chapters 5-9). Despite its important contribution, the materials science approach is inadequate to explain the hidden cultural reality such as ideas, beliefs, and symbolism critically associated with the process of iron and steel production.

3.3.2 Social Constructivist/ Constructionist Approach

Social constructivists believe that scientific knowledge is not purely objective, but is at least partly or entirely socially constructed (Johnson 1999: 45, see also Johnson 2010). This approach is relevant for this study, because technological choices of (later) iron and steel production were influenced partially or wholly by the society in terms of the social structure, people's beliefs and symbolism, and prior technological choices (see Killick 2004b: 571). Iron and steel production was inherited on a family basis- a father trained his sons or close relatives-, and the knowledge was passed on by word of mouth (e.g. Wembah-Rashid 1969: 69). It follows that in order to understand the process of iron and steel production in its social setting, we inevitably have to study the ironworking societies using chaîne opératoires, ethno-archaeological, historical, and

sociological methods (*cf*. Killick 2004b). To this end, one should question and interview the descendants of the smelters, because the actual (prehistoric) smelters are almost gone (*cf*. Killick 2004a; Barndon 2004). For the purpose of this work, the social constructivist/ constructionist approach has been used to explore the linkage between iron and steel production and pregnancy and child-delivery process among the Bena, Hehe, and Matengo (*cf*. Mumford 1943; Ndunguru 1972; Kapinga 1990; see Chapter 2). However, one of the critiques to this approach in archaeology is that it is less appropriate for the study of early metallurgy, because the descendants of the ironworkers might have partly or completely forgotten the basic knowledge of the culture and technology of iron and steel production, or there may be only sparse material culture of the early technology for comparative analysis.

3.3.3 Chaîne Opératoire Approach

Renfrew and Bahn (2012: 577) define chaîne opératoire as an ordered chain of actions, gestures, and processes in a production sequence that led to the transformation of a given material toward the finished products (for other definitions, *cf*. Cresswell 1990: 46; Sillar and Tite 2000: 4; Schlanger 2005: 31). This approach is relevant to the study of iron and steel production, because it helps us to infer back from the slags, furnaces, tuyères, and pottery to the whole procedure of iron and steel production including the preparation of raw materials (e.g. ores, charcoal, (re)production and protection medicines, clay), the selection of the smelting and refining sites, the ritualistic performances or celebrations, the construction and manufacturing of furnaces, tuyères, and pottery, the symbolism, the actual smelting and refining exercises (bellowing, tapping out slag, checking progress), the actual iron or steel collection, the celebratory or ritualistic performances, the forging (utility or symbolic) implements, and the use (and discard) of the tools (see also Barndon 2004: 92; Appendix 3.1). By following and

examining closely this chain, chaîne opératoire helps us to study technology, style, society, and culture flexibly and comprehensively (*cf*. Martinón-Torres 2002: 39), and by extension, we are able to appreciate the role of cultural and social issues in the realm of iron and steel production. To put it in the words of Sillar and Tite (2000: 17), in order to understand fully the technological choices that were made in the past, one needs to consider the full trajectory of the chaîne opératoire for the production of the object within its overall life cycle. In this study, this approach has been used to demonstrate the presence of a three stage (smelting→refining→smithing) iron and steel production process in Ufipa and Unyiha as opposed to a two stage (smelting→smithing) process followed in Umatengo, Uhehe, and Ubena societies (see Chapters 5-9). It is noteworthy; however, that the chaîne opératoire was developed for the study of stone artefacts, and it is less suited for non-process-oriented reconstructions (*cf*. Schlanger 2005: 28).

3.3.4 Symbolic and Structuralist Approaches

Symbolism of archaeological materials or phenomena refers to the study of secondary meanings of the material or phenomena beyond the primary (often technical or functional) use (*cf*. Hodder 2005: 254). Structuralism is concerned specifically with the symbolic significance of the archaeological material or phenomena (*cf*. Wylie 1982: 39, Miller 1982: 20). The approaches urge archaeologists to resist the appeal of cautious restriction of enquiry to observation, and endorse a process of reaching beyond what has been made accessible characterising a distinctive enquiry (*cf*. Wylie 1982: 46). Going beyond utility functions of the materials is vital, because as Leach (1973: 763) reasonably puts it, archaeological materials or phenomena are not things in themselves, nor are they just artefacts - things made by people - they are representations of human ideas that researchers must give due attention to in the pursuit of an adequate account of the materials. This approach has been employed, because iron and steel production was

symbolically equated to the (re)production (e.g. pregnancy and child-delivery) process (see Collect 1993; Herbert 1993; Schmidt 1997a; Reid and McLean 1995; Haaland 2004; Mapunda 2010). Specific for this study, the approaches are used to explain several aspects of iron and steel production process including: the decorated Bena iron production furnaces with (women) breasts (*cf*. Chapter 9), the excavated pottery at the bottom of the Matengo furnaces, and the ceramic containers (*cf*. Chapter 8) from the Kalenga smelting sites, the 'rake holes' of the iron furnaces as *child doors*, the location of the rake holes and furnaces on the western side of termite mounds in Ufipa and Unyiha, and the seclusion of iron and steel production activities from the settlements (e.g. Mumford 1943; Willis 1966; Ndunguru 1972). One of the problems of studying secondary meanings of the archaeological record is that they are mostly not open for scientific, empirical research for testing, because they are never accessible to direct inspection. In sum, the process of iron and steel production can be explained using both materials science and non-materials science approaches. This helps to explain both the description and characterisation of the material properties of artefact and to study how the material properties intervened in the social lives of people (Jones 2004: 335).

3.4 Summary

This chapter aimed at reviewing the literature related to the research topic, which has been done through the discussion of the previous and most relevant information to the current work. The review was based on the specific research objectives. It has been able to establish existing academic gaps that provide the rationale for this work. Also, the basis for the selection of the theoretical approaches for this study has been discussed. The next chapter presents the methodology used for this study.

4. Applied Methodology: Rationale for the Selection of the Research Area, Field, Experimental, and Laboratory Methods

4.1 Preamble

For the sake of clarity, this chapter is divided into four parts: research area selection, field data collection methods, experimental or rather field test briquettes (TBs) preparation and laboratory firing methods, and instrumental analytical techniques. Part one focuses on the reasons for the selection of the research area from different levels, that is, regional, district, ward, village, and site scales. Part two focuses on the field methods applied to discover sites, assess temporal and spatial distribution of the sites, and examine field data macroscopically. The field methods include ethnographic inquiries, surface walkover archaeological surveys, sub-surface detection, excavation, mapping as well as macroscopic attribute analysis. Part three examines TBs for the purpose of comparing them in terms of the chemical data with the technical ceramics, with a view to improve our understanding of the clay sources, and find out if there was an intentional selection of different clays for different technical functions. Lastly, part four focuses on the instrumental analytical techniques used to generate chemical and mineralogical data for this work. The techniques include X-ray fluorescence, optical microscopy, and electron microscopy. In addition, this chapter assesses the quality of the chemical data generated by X-ray fluorescence and electron microscopy methods.

4.2 Selection of the Research Area

4.2.1 Level 1: Selection of the Southern Highlands of Tanzania

The selection of the main research area was based on two factors. The first was to rectify the archaeological research imbalance in Tanzania, because the southern highland zone is almost archaeologically *terra incognita*. The second but equally important factor was the need to examine a good representation of the (macroscopic) variation of iron and steel production in Tanzania. According to the reviews by Chami (1994, 2005), Mapunda (1995b), and Masao (2005), the distribution of archaeological research in (mainland) Tanzania is uneven. The northern (e.g. Kilimanjaro, Arusha, Manyara, Kagera), central (e.g. Dodoma), coast, and littoral zones have apparently received more research attention than others. This is especially the case for the southern highlands of Tanzania, disregarding the Stone Age research in Iringa region (e.g. Isimila and Kalenga) and the ironworking research in northwestern Rukwa region (*cf*. Barndon 2004; Willoughby 2007; Biittner 2011; Mapunda 2010; Bushozi 2011). Some scholars (e.g. Mapunda 1995b; Masao 2005) have listed the factors for the disparity of the archaeological research in Tanzania including:

(1) financial problems,

(2) nature of the cultural remains (visible versus invisible),

(3) national cultural policy issues, and

(4) fewer (local) archaeologists in Tanzania.

It is difficult to understand that the southern highlands zone including Rukwa, Mbeya, Ruvuma, and Iringa (administrative) regions (Figure 4.1) continue to be archaeologically and archaeometallurgically poorly understood. To this end, and in order to even up the research disparity, the southern highland zone was selected for this work. Secondly and as noted above, the southern highlands zone has been selected as it

has an overall good representation of the (macroscopic) variation of recent iron and steel production furnaces. In Tanzania, there are a variety of iron and steel production furnaces, which include tall furnaces in excess of 3 m, shaft furnaces about 1.5 m, shorter furnaces about 1 m, and the shortest furnaces about 50 cm. These furnaces were generally made from clay lumps (e.g. Greig 1937), bricks (e.g. Schmidt 1997a), slabs (De Rosemond 1943), and clay rolls (e.g. Lyaya 2012). To crosscut this variation of the furnaces, the southern highlands of Tanzania, with the best representation of furnace types, were selected.

Figure 4.1: Map of the Southern Highlands (in pink and white) of Tanzania showing Rukwa, Mbeya, Ruvuma, and Iringa regions (Modified from ESRI elevation data derived from SRTM).

4.2.2 Level 2: Selection of Five Districts from the Southern Highlands Zone

Five administrative districts were selected, namely, Sumbawanga from Rukwa, Mbozi from Mbeya, Mbinga from Ruvuma, and rural Iringa and Njombe from Iringa. In order to ensure that all the different types of iron and steel furnaces were fully represented, one district represents one specific type of iron and steel furnaces. With this purpose in mind, the tall furnaces of about 3 m (e.g. Greig 1937; Brock and Brock 1965) were selected from Sumbawanga and Mbozi districts, because the two areas practised a similar iron and steel production technology (see Brock and Brock 1965; Mapunda 2010), and specifically aimed at comparing the iron and steel production processes of the two districts. The third district was Mbinga, chosen to represent the 1.5 m tall iron and steel production furnaces in the area (see Kapinga 1990). Although another district called Ludewa (of Iringa region) used similar 1.5 m tall iron smelting furnaces (see Barndon 2004), I chose the former (Mbinga) district, because the latter (Ludewa) has received relatively more archaeometallurgical research attention than the former (for example, see Barndon 2004; Schmidt 2006). Fourthly and for the case of the short iron furnaces of about 1 m, Njombe district from Iringa region was selected, because it is archaeometallurgically *terra incognita* compared to Makete and Ludewa districts, the other districts of the Iringa region with similar iron furnace designs (*cf*. Barndon 2004; Schmidt 2006; Mapunda 2010). In addition, the latter districts are relatively less accessible by road transport than the former, which is located off the Dar es Salaam-Songea Road. The fifth and last district is Rural Iringa, which was selected to represent the supposedly shortest iron furnaces of approximately 50 cm high, and made up of clay rolls.

4.2.3 Level 3: Selection of Seven Wards from the Five Districts

The first four administrative wards were selected from Mbozi and Mbinga districts, of which Itaka and Kapele wards were from the former, and Kigonsera and Lituhi wards were from the latter. The other three wards came from the remaining districts, that is, Pito from Sumbawanga, Kalenga from Rural Iringa, and Njombe ward from Njombe district. Of all the seven wards, five including Pito, Itaka, Lituhi, Kalenga, and Njombe were selected, because in these areas there were initial archaeological and ethnographic information on ironworking to guide our fieldwork investigation (see e.g. Mapunda 2001, 2010; Barndon 2004; Lyaya 2007, 2008b, 2012). The 6th (Kigonsera) ward was chosen, in order to provide data for comparing it with initially the Litembo ironworking technology (see Kapinga 1990), and then the ancient iron production process of the Lituhi ward (Mapunda and Burg 1991; Mapunda 1991, 2001). On the other hand, the 7th (Kapele) ward was selected, in order to explore the spatial distribution of the three stage process in Mbozi (Brock and Brock 1965), and to compare the iron and steel production furnaces of this area to Itaka ward, both of the Mbozi district.

4.2.4 Level 4: Survey of 23 and Selection of 12 Villages from the 7 Wards

I surveyed twenty-three villages of the seven wards, in order to establish the scale of production of iron and steel in the research area. Of the twenty-three villages, six were from Pito, five from Itaka, two from Kapele, five from Kigonsera, one from Lituhi, and two each from Kalenga and Njombe wards (for the names, location, and individual site details, see Chapters 5-9 and the relevant appendices). The survey involved recording, mapping, and examining all the materials including furnaces, tuyères, slags, and pottery encountered in the twenty-three villages. Of all, samples for further examination were selected from twelve villages including three villages (Mkumbi, Kamafupa, and Tupa) from Pito ward, three villages (Itaka, Shihando, and Malolo) from Itaka ward, one

village (Ntuha) from Lituhi ward, one village (Mkulusi) from Kigonsera ward, two villages (Msete and Nundu) from Njombe ward, and two villages (Ngongwa and Magubike) from Kalenga ward (see Chapters 5-9). These twelve villages were selected based on their better material composition and representation of the sites, and also the likelihood that the respective village sites represent a large scale production of iron and steel.

4.2.5 Level 5: Selection of twenty-four Sites from the twelve Villages

From the twelve sample villages, twenty-four sites were selected for microscopic sample examination. It was aimed at ensuring a good representation of the sample of the technological processes of the villages. To this end, sites were sampled depending on their material composition in terms of the furnaces (complete or broken), slags, tuyères, and pottery. To elucidate, sites with minimum material composition were not sampled in favour of those with maximum composition and better material representation. Also, in order to investigate the temporal variation of iron and steel production process, some sites were purposely selected from specific archaeological contexts. For example, the ancient Ntuha site from Lituhi ward and Magubike site #1 from the Kalenga ward were selected to be compared to the recent Mkulusi sites and Magubike #2 and Ngongwa sites respectively (see Chapters 7 and 8). In addition, for examination of the spatial variation of the technology, at least two sites were selected from each of the twelve villages for comparison purposes (see Chapters 5-9). Lastly, most of the smelting and refining sites were systematically selected based on proximity, because it is assumed that refining processes were situated next to the smelting furnaces (e.g. Greig 1937; Barndon 2004; Mapunda 2010). For example, smelting sites # 2 and 3, and refining sites # 4 and 5B from Mkumbi village were selected, because they were contiguous to each other.

4.3 Field Data Collection Methods

4.3.1 Ethnographic Inquiries

I started with ethnographic inquiries, because most of the study villages had not been surveyed before this project, and hence, I wanted to understand people's awareness in archaeological heritage, and in particular, knowledge of the ironworking process. First of all, I reported to the ward executive officers (WEOs), who requested respective village leadership to list for us informants that would be interviewed about the ironworking process (see the guiding questionnaire in Appendix 4.1). The selected informants included senior elders (known as *wazee* in Swahili), junior elders, and youths. They all claimed being aware of the recent ironworking technology in some way, and would be able to locate some iron and steel production sites in and around the villages.

Once the informants had been selected, I met them individually for the purpose of screening and to therefore identify more relevant informants for the inquiry on recent ironworking technology. The names and other details of the informants of this study are presented in Appendix 4.2a-e. Next I did one-to-one interviews (Figure 4.2) with the screened informants at their homes. This stage was followed by a focussed group discussion (FGD) stage (Figure 4.3), where all the interviewed informants formed groups for more in-depth discussion. After these stages, I conducted public archaeology talks (Figure 4.4), in order to introduce ourselves as a research team to the general public. This also allowed us to get extra oral information on ironworking and to raise people's awareness of the heritage sites for protection, preservation, and conservation purposes. Finally it allowed us to explore and discover archaeological and ironworking sites through so-called informants-led discovery.

Figure 4.2: Author interviewing Mzee Jonas Elia Mwanakulya (77 yrs old) from Itaka village, Mbozi

Figure 4.3: Author leading a FGD with informants from Minazi village, Mbinga

Figure 4.4: Samwel David (UDSM undergraduate student, 2009) delivering a talk on what is archaeology to Katumba-Azimio villagers in Sumbawanga

Following the interviews and the formal talks, I was shown some archaeological sites by the informants. These were examined and recorded. Through the informants-led discoveries, I was able to record 59 ironworking sites, which included smelting, refining, smithing, and ore source sites equivalent to 30% of the total discovered and recorded sites by this project (for the details of individual sites, see Chapters 5-9). The next task was to archaeologically survey other areas, in order to discover other archaeological sites.

4.3.2 Surface Walkover Survey Strategy

Surface walk-over surveys were possible through the aid of undergraduate students from the University of Dar es Salaam in the name of Archaeological Field School Training, 2009 through 2012 (Figure 4.5). Depending on the nature of the areas in terms of accessibility, safety, and visibility, I employed a systematic survey strategy in four wards, and an unsystematic survey approach in three wards (for details on the differences of two, see Renfrew and Bahn 2012: 75-78; see also Shennan 1997, chapter 14; Orton 2000, chapter 2). The former approach involved use of transects, whereby the

surveyors lined up, five metres apart from each other, and while surveying I moved from south to north (Figure 4.6). The latter involved walking over and around passable and safe areas, but both aimed at not missing out any sites. Through systematic and unsystematic survey approaches, I discovered 136 archaeological sites, equivalent to 70% of all sites (for details on the sites, see Chapters 5-9).

Figure 4.5: UDSM undergraduate students Archaeological Fieldschool Trainees 2009-2012

Figure 4.6: Systematic survey underway in Pito ward, Sumbawanga in 2009

As well as discovering the sites, the walkover survey included:

(1) recording the location and elevation of the sites using a GPS and total station (Figure 4.7), based on which I was able to produce contour maps of some sites (see Chapters 8-9),

(2) measuring the area, distances to nearest water and ore sources of the sites,

(3) meticulous search for less visible especially smithing sites (Figure 4.8),

(4) photographing materials and features,

(5) examining material composition and macroscopic characteristics of the sites, and

(6) collecting furnace wall, tuyère, slag, ore (Figure 4.9), and pottery samples for microscopic examination.

The macroscopic examination of the materials specifically involved measuring height, diameters, and size and number of the tuyère ports of the smelting furnaces. The nature of the proximal ends of the tuyères, and measuring the length, weight, and diameters of the tuyères were also noted. The types of smelting, refining, and smithing slags were classified based on morphology, and measuring weight and size (maximum length and width) of the slags. Finally the examination involved isolating decorated from

undecorated pottery (for the results of the macroscopic attributes analysis, see Chapters 5-9).

Figure 4.7: Contour mapping underway using a total station

Figure 4.8: In search for smithing slags (e.g. scales and droplets) in Kigonsera, Mbinga

Figure 4.9: Salum Muya (UDSM undergraduate 2010) collecting black (magnetite) sands at the shore of Lake Nyasa, Mbinga. Note the chemical data of the magnetite sands did not match with the slag chemical data, and hence the results are not reported

4.3.3 Sub-surface Survey Strategy

4.3.3.1 Shovel test pits

I dug at least two shovel test pits (STPs) in every surveyed village, for the purpose of testing the sub-surface distribution of the materials, because most of the surface sites often contained large heaps of smelting or refining debris. The STPs were 50 cm by 50 cm wide (Figure 4.10), oriented to the north, and dug down to between 60-80 cm. Unfortunately, none of the STPs retrieved stratified data, although 0-20 cm levels occasionally contained similar materials as on the surface.

Figure 4.10: Frida Kombe (UDSM undergraduate 2009) digging an STP in Kamafupa, Sumbawanga

4.3.3.2 Magnetometer survey

This technique was employed in two wards (Njombe and Pito) for two specific reasons. First, to verify oral accounts that nearby Nundu smelting and smithing sites in Njombe were hidden or rather buried smelted iron during the banning of smelting activities in the 20th century (e.g. John Akin Fute, interviewed on the 15th September, 2011). Although I conducted intensive and extensive systematic survey in and around the suspected region (Figure 4.11), I found no buried iron blooms only a burial. Second, I conducted magnetometer survey in Kamafupa, in order to establish the settlements of the people who smelted and refined iron at Kamafupa village. Unfortunately, I encountered no settlement features in and around the sites suggesting that the smelters (and refiners) isolated themselves from the settlements, or rather the general public (see also Greig 1937; Wise 1958; Wembah-Rashid 1969).

Figure 4.11: Magnetometer survey in practise: Jo Mwandambo (left), Anitha Msaki (middle), and Salum Muya (right), all UDSM undergraduates 2010

4.3.4 Excavation

This involved a systematic and methodical digging of the past remains (Figure 4.12), which aimed at retrieving buried archaeometallurgical data. Four sites were selected for excavation: Kamafupa, Mkumbi, Mkulusi, and Ntuha villages. Excavation of Kamafupa, Mkumbi both in Sumbawanga, and Mkulusi in Mbinga aimed at investigating whether buried ritual or medicinal pots were placed at the bottom of the smelting furnaces. No buried pots were retrieved from Sumbawanga smelting furnaces bases, although there were large potsherds buried at the furnace bases of Mkulusi #1 and #7 sites. I also excavated Ntuha site (mid 1st millennium AD, see Mapunda and Burg 1991: 35), in order to get ancient archaeometallurgical data for comparison with the recent ironworking of the Matengo (see Kapinga 1990). All the excavation units measured 1 m by 1 m, and were oriented to the north (Figure 4.13). Sub datum point (SDP) was established at the highest corner of each Unit for correct levelling measurements, levels were 10 cm each, and the Units were excavated down to the

sterile level. Excavated soil was screened (Figure 4.14) to pick up every small material otherwise not seen by the excavators in the trench. Recording, sorting, and bagging the materials were simultaneously done. Before backfilling the trenches, wall profiles were drawn (Figure 4.15).

Figure 4.12: Sarita Mamseri (left) (MA student at SOAS) and Khatibu Tagalile (UDSM undergraduate 2010) excavating level 3 of Unit 3 of the Ntuha site in Lituhi, Mbinga

Figure 4.13: Unit 3, Ntuha (IiJc-4) site showing its orientation and the sterile level

Figure 4.14: Pamela Felix (left), Salum Muya (middle), and Ditrick Chalamila (right) (UDSM undergraduates 2010) screening and sorting artefacts

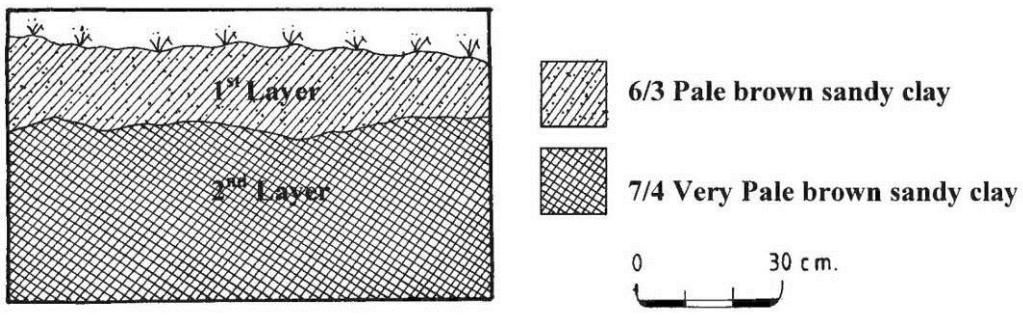

Figure 4.15: The northern wall profile of Unit 3, Ntuha (IiJc-4) site, Mbinga

4.4 Test Briquettes Preparation and Laboratory Firing

TBs were prepared and examined, in order to improve our understanding of the reasons for locating the Ufipa (Sumbawanga) smelting furnaces next to termite mounds (e.g. Barndon 2004; Mapunda 2010), and on the other hand, I wanted to understand the source of clays for the furnace clay rolls, and the use of the working place (WP) depression in Uhehe (Kalenga) iron production sites (e.g. Lyaya 2012). To this end, I prepared, examined, and compared the refractory quality and chemical composition of

the TBs to the real technical ceramics (for full results, see Chapter 5 for first case (Ufipa), and Chapter 8 for the other case (Uhehe)).

4.4.1 Preparation

Eight sites were selected from Ufipa, and one site (that is, Ngongwa smelting site #1) from Uhehe. Of the eight sites, four were from Mkumbi village, and two from each Kamafupa and Tupa villages. For the purpose of comparison, of the four sites from Mkumbi, two were each refining and smelting sites, and of the two sites from each Kamafupa and Tupa, one was a refining and the other a smelting site. From each termite mound, or the WP depression for the case of the Ngongwa site, I dug three spots and collected clay to make TBs using water. The fresh TBs, all measuring 10 cm long, 6 cm wide, and 2 cm thick, were labelled, sun-dried for two days on plastic bags (Figure 4.16), and shipped to London for laboratory firing experiments.

Figure 4.16: Fresh TBs from Mkumbi refining site

4.4.2 Laboratory Firing Experiments

The TBs were fired, in order to compare them with the technical ceramics. On the 18th October 2011, and for the purpose of the firing experiment, a small piece was broken

from each of the TBs, re-dried, to ensure a full removal of the water of plasticity, in the Binder main laboratory furnace at 105 ^{o}C overnight (Figure 4.17). On the 19th October 2011, the TBs from Mkumbi village were fired up to 900 ^{o}C in the Lenton (oxidising) furnace for three hours: 1st hour up to 100 ^{o}C, 2nd hour up to 700 ^{o}C, and the 3rd up to 900 ^{o}C. On the 20th October 2011, it took five hours to re-fire the Mkumbi TBs up to 1200 ^{o}C, and were left at the maximum temperature for 1 hour. None of them bloated at this temperature, and assuming a minimum smelting temperature of about 1200 ^{o}C (see Childs 1989a: 28), I decided to fire the other TBs from Kamafupa, Tupa, and Ngongwa up to this limit. On the 21st October 2011, the Kamafupa and Tupa TBs were fired up to 1200 ^{o}C for five hours, and were left at this temperature for 1 and half hours. On the 22nd October 2011, I fired the Ngongwa TBs using the same procedure, although they were left at the maximum temperature for 2 hours. None of the TBs bloated, suggestive of good refractory quality for the iron and steel production process (see Childs 1989a: 29, 1989b: 149).

Figure 4.17: TBs from Sumbawanga fired at 1200 ^{o}C in the Laboratory furnace

4.5 Analytical Techniques

4.5.1 Energy Dispersive X-ray Fluorescence (ED-XRF) Spectrometry

4.5.1.1 The principle

X-ray fluorescence spectrometry operates on the principle that primary X-rays usually produced by an X-ray tube are struck upon a sample to create inner shell vacancies in the atoms of the surface layers (e.g. Pollard *et al*. 2007; Pollard and Heron 2008). The vacancies de-excite with the production of a secondary (*fluorescent*) X-ray with energy characteristic of the elements present in the sample, and, some of these characteristic X-rays escape from the sample and are counted and their energies measured (see also Goffer 2007: 35; Pollard *et al*. 2007: 101). It is the comparison of these energies with

known values for each element that allows the elements present in the sample to be identified and quantified (Pollard *et al*. 2007: 101). Based on how they characterise the secondary radiation, there are two forms of X-ray fluorescence spectrometers, namely, wavelength dispersive (WD-XRF) and energy dispersive (ED-XRF) (e.g. Pollard *et al*. 2007). The former measures wavelength, while the latter measures the energy of the fluorescent X-ray (e.g. Pollard *et al*. 2007: 102; Pollard and Heron 2008: 42). I used a *polarising* ED-XRF spectrometer available in our department, which is analytically better than the conventional ED-XRF spectrometer, and, it is capable of detecting data from all elements simultaneously, and hence it is quicker than the WD-XRF, but at the expense of poorer resolution (see Pollard *et al*. 2007: 104; Pollard and Heron 2008: 42-43).

4.5.1.2 Preparation of pressed pellets

Small, good and clean specimen search of about 10-20 g were cut from slag, furnace wall, tuyère, pottery, and test briquette (TB) samples, and resized to small pieces using an abrasive diamond tile cutter. These were dried, and crushed into smaller pieces using steel mortar and pestle. A Retsch PM 100 Planetary Ball milling machine, with five tungsten carbide grinding balls, was set up at 500 rpm speed and 1.78 kg counterweight to powder the slag sample to less than 50 µm grain size for five minutes. Technical ceramics were similarly powdered using five agate grinding balls, at 450 rpm speed, and with 2.60 kg counterweight for 6 minutes. The powder was put into glass sample vials, covered with a double clinical tissue held by plastic bands to avoid contamination, and dried in a Binder main laboratory oven overnight at 105 ^{o}C to remove analytical loss by water. Next the analyte sample (5-8 g) and wax were mixed to a ratio of 9:1 in a dedicated balance, and thoroughly mixed by an agate mortar and pestle. They were then

pressed into pellets in aluminium cups at 15 tonnes force for 2.5 minutes using the Specad pressing machine, and finally they were labelled before the actual analysis.

4.5.1.3 Analysis

The UCL Institute of Archaeology Spectro Lab XPro 2000 instrument was loaded for each batch with 15 samples and 3 or 4 reference materials (RMs) for the technical ceramics and slags respectively. The RMs for the technical ceramics were the NBS 679 Brick Clay, SARM 69 Ceramic-1, and SO-1 Reference Soil (see Appendix 4.3a-c), while for the slag samples the BCS 301 Lincolnshire Iron Ore, BCS 381 Basic Slag, ECRM 681 Iron Ore, and Swedish Slag (Hjärthener-Holdar 2001) RMs were used (see Appendix 4.4a-d). Each set of the samples and RMs was analysed three times, in order to assess the precision of the resultant data. In terms of methods, I selected the Turbo Quant (TQ-0261d) method for the analysis of the technical ceramics (Schramm and Heckel 1998), and Slag_Fun evaluation method for the analysis of the slag samples (see Veldhuijzen 2003). The Slag_Fun method that employs five polarising targets, is optimised for iron-rich materials, and was calibrated for pressed pellets (Veldhuijzen 2003). According to Veldhuijzen (2003), a *polarising* ED-XRF reduces the spectral background interferences, and so improves the quality of the data by lowering the detection limits of the normal ED-XRF machine to tens of ppm (see also Iles 2011: 123). The results were automatically reported as stoichiometric oxides by an in-built XPro software, although I (manually) re-converted Fe_2O_3 to FeO by multiplying it with 0.8993, because with smelting temperature of around 1200 ^{o}C and strongly reducing conditions, high iron oxides such as haematite (Fe_2O_3) must have been reduced to wüstite (or even to iron and steel) as exhibited mineralogically (see the mineralogical data presented in Chapters 5-9). The results were normalised to 100 wt% for simple

comparison with other published data, but the analytical totals are reported for further reference (for full results, see Chapters 5-9 and relevant appendices).

4.5.1.4 Data quality assessment

In order to assess the quality of the resultant data in terms of precision and accuracy, the measured values (MVs) for the RMs were compared to the certified values (CVs). To assess the precision of the data, standard deviation (SD) of the repeated measurements was calculated, and compared to the MVs to obtain the coefficient of variation (CoV) in percent (i.e. CoV=100(SD/MV). To check the accuracy, the difference between MV and CV (herein referred to as absolute accuracy, and abbreviated as Abs. δ in the tables below) was compared to the CVs, in order to calculate the percentage relative errors (herein referred to as relative accuracy in %, and abbreviated as Rel. δ in the tables below) of the data. The results of the precision and accuracy assessment are presented in tables 1 through 3 (see Table 4.1, Table 4.2, Table 4.3) for the technical ceramics, and tables 4 through 7 (see Table 4.4, Table 4.5, Table 4.6, Table 4.7) for the slag RMs. It should be noted that the top part of each of the tables shows the initial assessment of the precision and accuracy of the data, and the bottom parts present the final or rather second assessment of the precision and accuracy of the data. The second assessment was critically necessary, because the initial assessment revealed that although the major and minor oxides (except soda) were consistently precise, with acceptable precision errors below 10 % and in most cases well below 2%, more than half of the oxides were surprisingly inaccurate, with relative errors above 10 %. To elucidate, out of 13 oxides reported in each of the tables, silica and lime alone were consistently precise and accurate throughout the RMs, and on average, 3 out of the 13 oxides were accurate for the technical ceramic RMs, and 4 out of 13 oxides were accurate for the slag RMs. I would have not used such data with dubious quality for the purpose of this research

project, and hence, I applied an empirical correction factor (CF), based upon the analyses of the RMs, to re-calibrate the data. It was possible to re-calibrate particularly the accuracy of the data, because the machine was consistently precise. I calculated and applied the correction factors (CFs) to the MVs as follows:

(1) Average the ratios of MVs to CVs of the three or four RMs respectively, to give the CFs

(2) Divide the MVs by the CFs for all oxides,

(3) Normalize the data to 100 wt%,

(4) Re-calculate the precision and accuracy of the MVs, and

(5) Compare the differences in the precision and accuracy of the data.

The re-calibration by the CF technique as shown below significantly improved the accuracy of the data to acceptable levels of relative accuracy errors of less than 10%, and in most cases well below 5% for all the RMs. Phosphorous and chromium oxides are exceptions for the technical ceramics RMs, with unacceptable accuracy errors of 200% and 20% on average, and hence analytical data for these oxides will not be reported or used (see Chapters 5-9). For the case of the slag RMs, soda, sulphide, vanadia, and chromia were not reported in the archaeological sample data (see Chapters 5-9), because of the unacceptable relative errors of 40%, 60%, 56%, and 71% on average. Although magnesia showed poor accuracy as well, it was yet reported in the archaeological sample data, because it was typically found at levels detectable by SEM-EDS and thus its presence and relative concentration could be verified by this method (see SEM-EDS data quality assessment). Because the re-calibration via the correction factor(s) technique worked perfectly for the RMs, it was then applied to the real (ceramics and slags) data, with a view to recalibrate and produce acceptable high quality data (for full results, see Chapters 5-9).

Table 4.1: Normalised data quality assessment for the NBS 679 standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom= final assessment after application of the empirical correction factor

NBS 679	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	
16/01/2012	0.90	2.02	27.04	57.72	0.14	2.52	0.23	0.90	0.02	0.01	0.16	8.26	103.51
17/01/2012	0.98	2.11	26.98	57.81	0.14	2.52	0.23	0.88	0.02	0.01	0.16	8.07	103.29
18/01/2012	0.84	2.07	27.02	57.63	0.14	2.53	0.23	0.90	0.02	0.01	0.17	8.35	103.62
18/01/2012	0.96	2.10	26.90	57.78	0.14	2.52	0.23	0.89	0.02	0.01	0.16	8.21	103.42
19/01/2012	0.83	2.05	26.94	57.75	0.14	2.54	0.23	0.89	0.03	0.01	0.17	8.34	103.65
20/01/2012	0.79	2.14	26.94	57.72	0.14	2.53	0.23	0.89	0.02	0.01	0.17	8.32	103.63
23/01/2012	0.79	2.08	27.00	57.71	0.14	2.53	0.23	0.90	0.02	0.01	0.16	8.34	103.65
24/01/2012	0.82	2.07	26.91	57.76	0.14	2.55	0.23	0.90	0.02	0.01	0.17	8.33	103.64
24/01/2012	0.86	2.07	26.93	57.70	0.14	2.53	0.24	0.89	0.03	0.01	0.17	8.34	103.62
MV	0.86	2.08	26.96	57.73	0.14	2.53	0.23	0.89	0.02	0.01	0.16	8.28	103.56
CV	0.20	1.37	22.76	56.98		3.21	0.25	1.05		0.02		14.16	91.38
SD	0.07	0.04	0.05	0.05	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.09	
CoV %	**8**	**2**	**0**	**0**	**1**	**0**	**1**	**1**	**6**	**5**	**1**	**1**	
Abs. δ	0.67	0.71	4.20	0.75	0.14	-0.68	-0.02	-0.16	0.02	-0.01	0.16	-5.88	
Rel. δ %	**339**	**52**	**18**	**1**		**-21**	**-8**	**-15**		**-52**		**-41**	
CF	***4.39***	***1.40***	***1.21***	***0.97***	***0.27***	***0.77***	***0.87***	***0.79***	***0.77***	***0.59***	***0.65***	***0.56***	
16/01/2012	0.20	1.39	21.57	57.30	0.50	3.15	0.26	1.10	0.03	0.02	0.24	14.24	103.31
17/01/2012	0.22	1.45	21.57	57.52	0.51	3.16	0.26	1.09	0.03	0.02	0.24	13.94	103.06
18/01/2012	0.19	1.42	21.54	57.15	0.51	3.16	0.26	1.10	0.03	0.02	0.25	14.38	103.43
18/01/2012	0.21	1.44	21.48	57.41	0.50	3.16	0.25	1.09	0.03	0.02	0.24	14.17	103.21
19/01/2012	0.18	1.41	21.47	57.25	0.50	3.17	0.26	1.10	0.03	0.02	0.24	14.36	103.46
20/01/2012	0.17	1.47	21.47	57.23	0.51	3.17	0.26	1.09	0.03	0.02	0.25	14.33	103.45
23/01/2012	0.17	1.43	21.51	57.21	0.51	3.16	0.26	1.10	0.03	0.02	0.24	14.36	103.47

24/01/2012	0.18	1.42	21.45	57.27	0.50	3.19	0.26	1.10	0.03	0.02	0.24	14.34	103.45
24/01/2012	0.19	1.42	21.47	57.22	0.51	3.17	0.26	1.09	0.03	0.02	0.24	14.37	103.42
MV	0.19	1.43	21.50	57.28	0.51	3.17	0.26	1.10	0.03	0.02	0.24	14.28	103.36
CV	0.20	1.37	22.76	56.98		3.21	0.25	1.05		0.02		14.16	91.38
SD	0.02	0.02	0.05	0.11	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.14	
CoV %	**8**	**2**	**0**	**0**	**1**	**0**	**1**	**1**	**6**	**5**	**1**	**1**	
Abs. δ	-0.01	0.06	-1.26	0.30	0.51	-0.04	0.01	0.05	0.03	0.00	0.24	0.12	
Rel. δ %	**-3**	**4**	**-6**	**1**		**-1**	**3**	**4**		**-22**		**1**	

Table 4.2: Normalised data quality assessment for the SARM 69 standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

SARM 69	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	
16/01/2012	1.82	2.54	20.34	65.90	0.29	1.71	2.21	0.65	0.02	0.02	0.09	4.40	102.94
17/01/2012	2.01	2.55	20.36	65.73	0.28	1.71	2.21	0.65	0.02	0.02	0.09	4.37	102.95
18/01/2012	1.72	2.56	20.43	65.87	0.29	1.73	2.22	0.65	0.02	0.02	0.09	4.40	102.95
18/01/2012	1.91	2.56	20.32	65.81	0.29	1.72	2.22	0.65	0.02	0.02	0.09	4.39	102.95
19/01/2012	1.71	2.50	20.45	65.87	0.29	1.74	2.23	0.65	0.02	0.02	0.09	4.42	102.94
20/01/2012	1.77	2.55	20.38	65.86	0.29	1.73	2.22	0.65	0.02	0.02	0.09	4.41	102.94
23/01/2012	1.89	2.53	20.38	65.79	0.29	1.73	2.22	0.65	0.02	0.02	0.09	4.39	102.94
24/01/2012	1.68	2.57	20.47	65.88	0.29	1.71	2.22	0.64	0.02	0.02	0.09	4.40	102.94
24/01/2012	1.88	2.52	20.37	65.84	0.29	1.72	2.23	0.64	0.02	0.02	0.09	4.38	102.94
MV	1.82	2.54	20.39	65.84	0.29	1.72	2.22	0.65	0.02	0.02	0.09	4.39	102.94
CV		1.94	15.11	69.89		2.06	2.49	0.82		0.03	0.14	7.53	95.30
SD	0.11	0.02	0.05	0.05	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.02	
CoV %	**6**	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**7**	**3**	**1**	**0**	
Abs. δ		0.60	5.28	-4.05	0.29	-0.34	-0.27	-0.17	0.02	-0.01	-0.05	-3.14	
Rel. δ %		**31**	**35**	**-6**		**-16**	**-11**	**-21**		**-39**	**-34**	**-42**	

CF	***4.39***	***1.40***	***1.21***	***0.97***	***0.27***	***0.77***	***0.87***	***0.79***	***0.77***	***0.59***	***0.65***	***0.56***	
16/01/2012	0.41	1.78	16.56	66.74	1.05	2.19	2.52	0.81	0.03	0.03	0.14	7.75	101.46
17/01/2012	0.45	1.79	16.61	66.70	1.03	2.19	2.52	0.81	0.02	0.03	0.13	7.71	101.25
18/01/2012	0.39	1.79	16.61	66.67	1.06	2.21	2.53	0.81	0.03	0.03	0.13	7.73	101.53
18/01/2012	0.43	1.80	16.55	66.71	1.05	2.20	2.53	0.81	0.02	0.03	0.13	7.73	101.37
19/01/2012	0.38	1.76	16.63	66.65	1.06	2.22	2.53	0.81	0.02	0.03	0.14	7.76	101.56
20/01/2012	0.40	1.79	16.58	66.68	1.05	2.21	2.53	0.81	0.03	0.03	0.14	7.76	101.50
23/01/2012	0.43	1.77	16.60	66.68	1.05	2.21	2.53	0.81	0.03	0.03	0.13	7.72	101.39
24/01/2012	0.38	1.80	16.65	66.68	1.06	2.18	2.53	0.81	0.03	0.03	0.13	7.73	101.53
24/01/2012	0.42	1.77	16.59	66.73	1.05	2.20	2.54	0.81	0.03	0.03	0.14	7.70	101.39
MV	0.41	1.78	16.60	66.69	1.05	2.20	2.53	0.81	0.02	0.03	0.14	7.73	101.44
CV		1.94	15.11	69.89		2.06	2.49	0.82		0.03	0.14	7.53	95.30
SD	0.03	0.02	0.03	0.03	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.02	
CoV %	**6**	**1**	**0**	**0**	**1**	**1**	**0**	**0**	**7**	**3**	**1**	**0**	
Abs. δ	0.41	-0.16	1.49	-3.19	1.05	0.14	0.04	-0.01	0.02	0.00	0.00	0.20	
Rel. δ %		**-8**	**10**	**-5**		**7**	**2**	**-1**		**2**	**0**	**3**	

Table 4.3: Normalised data quality assessment for the SO-1 standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

SO-1	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	
16/01/2012	5.18	5.77	21.14	57.66	0.12	2.42	2.15	0.69	0.02	0.02	0.08	4.76	102.92
17/01/2012	5.28	5.80	21.09	57.61	0.12	2.39	2.13	0.68	0.02	0.02	0.08	4.77	102.92
18/01/2012	5.14	5.75	21.07	57.77	0.13	2.41	2.14	0.69	0.02	0.01	0.08	4.78	102.91
18/01/2012	5.33	5.67	21.14	57.59	0.12	2.40	2.15	0.69	0.02	0.01	0.08	4.78	102.92
19/01/2012	5.35	5.79	21.10	57.50	0.12	2.41	2.14	0.68	0.02	0.01	0.08	4.78	102.91
20/01/2012	4.99	5.77	21.20	57.72	0.13	2.43	2.15	0.69	0.02	0.02	0.08	4.80	102.92
24/01/2012	5.45	5.77	21.13	57.46	0.12	2.39	2.12	0.69	0.02	0.01	0.08	4.76	102.92
23/01/2012	5.07	5.76	21.18	57.69	0.12	2.42	2.15	0.69	0.02	0.01	0.08	4.79	102.92
24/01/2012	5.08	5.76	21.22	57.67	0.12	2.41	2.15	0.69	0.02	0.01	0.08	4.79	102.92
MV	5.21	5.76	21.14	57.63	0.12	2.41	2.14	0.69	0.02	0.01	0.08	4.78	102.92
CV		4.16	19.24	59.77	0.15	3.51	2.73	0.96	0.02	0.02	0.12	9.32	92.14
SD	0.15	0.04	0.05	0.10	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	
CoV %	**3**	**1**	**0**	**0**	**1**	**1**	**1**	**0**	**5**	**5**	**1**	**0**	
Abs. δ	5.21	1.60	1.90	-2.14	-0.03	-1.10	-0.59	-0.27	-0.01	-0.01	-0.04	-4.55	
Rel. δ %		**39**	**10**	**-4**	**-19**	**-31**	**-22**	**-28**	**-23**	**-32**	**-36**	**-49**	
CF	***4.39***	***1.40***	***1.21***	***0.97***	***0.27***	***0.77***	***0.87***	***0.79***	***0.77***	***0.59***	***0.65***	***0.56***	
16/01/2012	1.21	4.21	17.89	60.71	0.46	3.22	2.55	0.89	0.02	0.03	0.12	8.71	97.60
17/01/2012	1.23	4.23	17.87	60.71	0.46	3.18	2.53	0.89	0.02	0.03	0.12	8.72	97.51
18/01/2012	1.20	4.19	17.82	60.79	0.47	3.20	2.53	0.90	0.02	0.02	0.12	8.74	97.66
18/01/2012	1.25	4.14	17.91	60.68	0.47	3.19	2.54	0.90	0.02	0.03	0.12	8.75	97.52
19/01/2012	1.25	4.23	17.88	60.61	0.47	3.21	2.54	0.89	0.02	0.03	0.12	8.75	97.47
20/01/2012	1.16	4.20	17.91	60.66	0.47	3.22	2.54	0.90	0.02	0.03	0.12	8.76	97.78

24/01/2012	1.28	4.22	17.92	60.64	0.47	3.19	2.51	0.90	0.02	0.03	0.12	8.72	97.37
23/01/2012	1.18	4.20	17.91	60.68	0.46	3.21	2.54	0.90	0.02	0.03	0.12	8.75	97.70
24/01/2012	1.18	4.19	17.94	60.67	0.47	3.20	2.54	0.89	0.02	0.02	0.12	8.75	97.68
MV	1.22	4.20	17.89	60.68	0.47	3.20	2.54	0.90	0.02	0.03	0.12	8.74	97.59
CV		4.16	19.24	59.77	0.15	3.51	2.73	0.96	0.02	0.02	0.12	9.32	92.14
SD	0.04	0.03	0.04	0.05	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.02	
CoV %	**3**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**5**	**5**	**1**	**0**	
Abs. δ	1.22	0.05	-1.35	0.92	0.32	-0.30	-0.20	-0.06	0.00	0.00	0.00	-0.58	
Rel. δ %		**1**	**-7**	**2**	**207**	**-9**	**-7**	**-6**	**2**	**18**	**1**	**-6**	

Table 4.4: Normalised data quality assessment for the BSC 301 standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

BCS 301	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	%	%
25/01/2012	0.76	2.79	10.02	11.98	0.95	0.77	0.42	29.23	0.22	0.14	0.02	1.30	41.39	102.87
26/01/2012	0.44	2.90	10.03	11.94	0.95	0.78	0.42	29.32	0.22	0.14	0.02	1.30	41.53	102.87
27/01/2012	0.31	2.90	10.01	11.96	0.95	0.77	0.42	29.28	0.22	0.14	0.03	1.31	41.70	102.87
30/01/2012	0.47	2.82	9.95	12.06	0.94	0.77	0.43	29.28	0.22	0.15	0.02	1.31	41.59	102.88
31/01/2012	0.28	2.79	10.04	12.01	0.94	0.77	0.43	29.12	0.23	0.14	0.03	1.30	41.92	102.88
01/02/2012	0.35	2.88	9.98	12.19	0.94	0.77	0.42	29.23	0.22	0.14	0.02	1.30	41.54	102.90
MV	0.43	2.85	10.00	12.02	0.95	0.77	0.42	29.25	0.22	0.14	0.02	1.30	41.61	102.88
CV	0.09	2.35	5.78	10.04	1.09	1.36	0.43	30.65	0.22	0.01		1.70	46.29	73.73
SD	0.18	0.05	0.03	0.09	0.01	0.01	0.00	0.07	0.00	0.00	0.00	0.00	0.18	
CoV %	**41**	**2**	**0**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**2**	**0**	**0**	
Abs. δ	0.34	0.50	4.23	1.99	-0.14	-0.59	-0.01	-1.41	0.00	0.13	0.02	-0.39	-4.68	

Rel. δ %	**357**	**21**	**73**	**20**	**-13**	**-43**	**-2**	**-5**	**2**	**958**		**-23**	**-10**	
CF	***2.80***	***0.84***	***1.63***	***1.18***	***0.96***	***1.23***	***0.90***	***1.01***	***0.94***	***3.47***	***0.70***	***0.74***	***0.86***	
25/01/2012	0.27	3.30	6.08	10.06	0.98	0.62	0.46	28.58	0.23	0.04	0.03	1.73	47.61	101.03
26/01/2012	0.15	3.42	6.08	10.00	0.97	0.63	0.46	28.59	0.23	0.04	0.04	1.73	47.65	101.29
27/01/2012	0.11	3.42	6.06	10.00	0.97	0.61	0.46	28.52	0.23	0.04	0.04	1.74	47.80	101.40
30/01/2012	0.16	3.33	6.03	10.10	0.97	0.62	0.47	28.55	0.23	0.04	0.03	1.73	47.73	101.28
31/01/2012	0.10	3.29	6.08	10.04	0.97	0.62	0.47	28.35	0.24	0.04	0.04	1.73	48.03	101.42
01/02/2012	0.12	3.40	6.05	10.21	0.96	0.62	0.46	28.49	0.23	0.04	0.03	1.73	47.64	101.33
MV	0.15	3.36	6.06	10.07	0.97	0.62	0.47	28.51	0.23	0.04	0.04	1.73	47.75	101.29
CV	0.09	2.35	5.78	10.04	1.09	1.36	0.43	30.65	0.22	0.01		1.70	46.29	73.73
SD	0.06	0.06	0.02	0.08	0.01	0.01	0.00	0.09	0.00	0.00	0.00	0.00	0.16	
CoV %	**41**	**2**	**0**	**1**	**1**	**1**	**1**	**0**	**1**	**1**	**2**	**0**	**0**	
Abs. δ	0.06	1.01	0.28	0.03	-0.11	-0.74	0.03	-2.14	0.02	0.03	0.04	0.04	1.45	
Rel. δ %	**61**	**43**	**5**	**0**	**-11**	**-54**	**7**	**-7**	**7**	**201**		**2**	**3**	

Table 4.5: Normalised precision and accuracy results for the BCS 381 standard. Note that measurements are the average of the 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

BCS 381	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	%	%
25/01/2012	1.51	0.02	0.88	10.99	14.79	0.57	0.15	50.05	0.31	0.81	0.28	2.53	17.11	102.94
26/01/2012	1.26	0.02	0.87	10.97	14.83	0.58	0.15	50.22	0.31	0.78	0.29	2.54	17.20	102.94
27/01/2012	1.35	0.03	0.89	10.98	14.82	0.59	0.14	50.17	0.31	0.79	0.29	2.54	17.10	102.93
30/01/2012	1.35	0.02	0.88	10.95	14.84	0.58	0.15	50.18	0.31	0.79	0.29	2.54	17.12	102.94
31/01/2012	1.66	0.02	0.89	11.05	14.68	0.58	0.15	49.61	0.31	0.77	0.28	2.50	17.48	102.94
01/02/2012	1.36	0.02	1.02	11.14	14.69	0.57	0.15	50.00	0.31	0.78	0.29	2.53	17.16	102.94
MV	1.42	0.02	0.90	11.01	14.77	0.58	0.15	50.04	0.31	0.79	0.29	2.53	17.19	102.94
CV		1.04	0.67	8.83	15.79	0.47		49.27	0.35	0.95	0.33	3.18	19.13	99.46
SD	0.14	0.00	0.06	0.07	0.07	0.01	0.00	0.22	0.00	0.02	0.00	0.01	0.15	
CoV %	**10**	**6**	**6**	**1**	**0**	**1**	**2**	**0**	**1**	**2**	**1**	**1**	**1**	
Abs. δ	1.42	-1.01	0.23	2.18	-1.01	0.11	0.15	0.77	-0.04	-0.16	-0.05	-0.65	-1.94	
Rel. δ %		**-98**	**34**	**25**	**-6**	**23**		**2**	**-12**	**-17**	**-14**	**-20**	**-10**	
CF	***2.80***	***0.84***	***1.63***	***1.18***	***0.96***	***1.23***	***0.90***	***1.01***	***0.94***	***3.47***	***0.70***	***0.74***	***0.86***	
25/01/2012	0.54	0.03	0.54	9.31	15.37	0.47	0.16	49.36	0.33	0.23	0.41	3.40	19.86	100.12
26/01/2012	0.45	0.03	0.53	9.27	15.37	0.47	0.16	49.43	0.33	0.22	0.41	3.40	19.93	100.33
27/01/2012	0.48	0.03	0.54	9.29	15.38	0.48	0.16	49.43	0.33	0.23	0.41	3.41	19.83	100.24
30/01/2012	0.48	0.03	0.54	9.26	15.40	0.47	0.16	49.43	0.33	0.23	0.41	3.41	19.85	100.25
31/01/2012	0.59	0.03	0.54	9.37	15.26	0.47	0.17	48.94	0.33	0.22	0.41	3.37	20.30	100.10
01/02/2012	0.48	0.03	0.62	9.43	15.25	0.46	0.16	49.29	0.33	0.22	0.41	3.40	19.90	100.18
MV	0.50	0.03	0.55	9.32	15.34	0.47	0.16	49.31	0.33	0.23	0.41	3.40	19.94	100.20
CV		1.04	0.67	8.83	15.79	0.47		49.27	0.35	0.95	0.33	3.18	19.13	99.46
SD	0.05	0.00	0.03	0.06	0.07	0.01	0.00	0.19	0.00	0.00	0.00	0.02	0.18	
CoV %	**10**	**6**	**6**	**1**	**0**	**1**	**2**	**0**	**1**	**2**	**1**	**0**	**1**	
Abs. δ	0.50	-1.01	-0.12	0.50	-0.45	0.00	0.16	0.05	-0.02	-0.72	0.08	0.22	0.81	
Rel. δ %		**-97**	**-18**	**6**	**-3**	**0**		**0**	**-6**	**-76**	**23**	**7**	**4**	

Table 4.6: Normalised data quality assessment for the ECRM 681 standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

ECRM 681	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	%	%
25/01/2012	0.13	1.97	22.27	23.99	2.28	0.33	0.55	4.52	0.48	0.15	0.07	0.23	43.04	102.78
26/01/2012	0.18	2.04	22.33	23.98	2.28	0.33	0.54	4.50	0.48	0.15	0.07	0.23	42.90	102.80
27/01/2012	0.29	1.99	22.39	23.94	2.27	0.33	0.55	4.50	0.48	0.15	0.07	0.23	42.82	102.80
30/01/2012	0.24	1.99	22.32	23.88	2.28	0.33	0.55	4.53	0.48	0.15	0.07	0.23	42.95	102.80
31/01/2012	0.04	2.14	22.10	23.96	2.27	0.33	0.55	4.51	0.48	0.15	0.07	0.23	43.17	102.82
01/02/2012	0.11	2.01	22.18	24.16	2.27	0.33	0.55	4.52	0.48	0.15	0.07	0.23	42.94	102.79
MV	0.16	2.02	22.26	23.98	2.28	0.33	0.55	4.51	0.48	0.15	0.07	0.23	42.97	102.79
CV	0.11	1.72	12.46	20.89	2.36	0.30	0.69	4.60	0.56	0.16	0.07	0.34	55.74	85.26
SD	0.09	0.06	0.11	0.09	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.12	
CoV %	**55**	**3**	**0**	**0**	**0**	**1**	**1**	**0**	**1**	**0**	**1**	**0**	**0**	
Abs. δ	0.05	0.30	9.81	3.09	-0.08	0.03	-0.14	-0.08	-0.08	-0.01	0.00	-0.11	-12.77	
Rel. δ %	**51**	**17**	**79**	**15**	**-3**	**9**	**-21**	**-2**	**-15**	**-5**	**1**	**-33**	**-23**	
CF	***2.80***	***0.84***	***1.63***	***1.18***	***0.96***	***1.23***	***0.90***	***1.01***	***0.94***	***3.47***	***0.70***	***0.74***	***0.86***	
25/01/2012	0.05	2.47	14.37	21.40	2.49	0.28	0.64	4.69	0.54	0.05	0.11	0.32	52.59	95.11
26/01/2012	0.07	2.56	14.42	21.40	2.49	0.28	0.63	4.68	0.53	0.05	0.11	0.32	52.46	95.04
27/01/2012	0.11	2.50	14.47	21.39	2.49	0.29	0.64	4.69	0.53	0.05	0.11	0.32	52.42	94.93
30/01/2012	0.09	2.51	14.42	21.32	2.50	0.28	0.64	4.71	0.54	0.05	0.11	0.32	52.53	95.03
31/01/2012	0.01	2.68	14.23	21.33	2.48	0.28	0.64	4.67	0.54	0.05	0.11	0.32	52.65	95.29
01/02/2012	0.04	2.52	14.31	21.55	2.49	0.29	0.64	4.69	0.54	0.05	0.11	0.32	52.47	95.12
MV	0.06	2.54	14.37	21.40	2.49	0.28	0.64	4.69	0.54	0.05	0.11	0.32	52.52	95.09
CV	0.11	1.72	12.46	20.89	2.36	0.30	0.69	4.60	0.56	0.16	0.07	0.34	55.74	85.26
SD	0.03	0.07	0.09	0.08	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.09	
CoV %	**55**	**3**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	
Abs. δ	-0.05	0.82	1.91	0.51	0.13	-0.02	-0.05	0.09	-0.03	-0.12	0.04	-0.02	-3.22	
Rel. δ %	**-43**	**47**	**15**	**2**	**6**	**-7**	**-8**	**2**	**-5**	**-71**	**52**	**-6**	**-6**	

Table 4.7: Normalised data quality assessment for the Swedish Slag standard. Note that measurements are the average of 3 runs, top part= initial assessment, and bottom part= final assessment after application of the empirical correction factor

Swedish Slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	%	%
25/01/2012	1.51	0.35	12.01	26.93	0.27	0.20	0.90	1.55	0.30	0.04	0.00	2.24	53.70	102.94
26/01/2012	1.28	0.32	12.00	26.94	0.27	0.19	0.89	1.55	0.30	0.04	0.00	2.24	53.95	102.94
27/01/2012	1.34	0.48	11.97	26.75	0.27	0.20	0.89	1.56	0.30	0.04	0.00	2.25	53.92	102.92
30/01/2012	1.29	0.33	11.91	26.91	0.27	0.20	0.90	1.56	0.30	0.04	0.00	2.25	54.03	102.95
31/01/2012	1.38	0.23	11.89	26.81	0.27	0.19	0.91	1.56	0.31	0.04	0.00	2.24	54.18	102.94
01/02/2012	1.46	0.52	11.92	26.95	0.26	0.20	0.89	1.55	0.30	0.04	0.00	2.24	53.66	102.94
MV	1.37	0.37	11.95	26.88	0.27	0.20	0.90	1.56	0.30	0.04	0.00	2.24	53.91	102.94
CV	0.59	0.40	7.20	23.97	0.25	0.10	0.96	1.42	0.30	0.03	0.01	3.03	61.74	103.17
SD	0.09	0.11	0.05	0.08	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.20	
CoV %	**7**	**30**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	
Abs. δ	0.78	-0.02	4.75	2.91	0.02	0.10	-0.06	0.14	0.00	0.02	-0.01	-0.79	-7.83	
Rel. δ %	**132**	**-6**	**66**	**12**	**7**	**103**	**-7**	**10**	**1**	**52**	**-78**	**-26**	**-13**	
CF	***2.80***	***0.84***	***1.63***	***1.18***	***0.96***	***1.23***	***0.90***	***1.01***	***0.94***	***3.47***	***0.70***	***0.74***	***0.86***	
25/01/2012	0.54	0.41	7.38	22.87	0.28	0.16	1.00	1.53	0.32	0.01	0.00	3.01	62.48	99.90
26/01/2012	0.46	0.39	7.36	22.84	0.28	0.16	0.99	1.53	0.32	0.01	0.00	3.02	62.64	100.09
27/01/2012	0.48	0.58	7.34	22.67	0.28	0.16	0.99	1.54	0.32	0.01	0.00	3.03	62.60	100.12
30/01/2012	0.46	0.40	7.30	22.79	0.28	0.16	0.99	1.54	0.32	0.01	0.00	3.03	62.71	100.15
31/01/2012	0.49	0.27	7.29	22.72	0.28	0.16	1.00	1.53	0.32	0.01	0.00	3.01	62.90	100.11
01/02/2012	0.52	0.62	7.32	22.86	0.27	0.16	0.99	1.53	0.32	0.01	0.00	3.02	62.37	99.99
MV	0.49	0.45	7.33	22.79	0.28	0.16	0.99	1.54	0.32	0.01	0.00	3.02	62.62	100.06
CV	0.59	0.40	7.20	23.97	0.25	0.10	0.96	1.42	0.30	0.03	0.01	3.03	61.74	103.17
SD	0.03	0.13	0.03	0.08	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.18	
CoV %	**7**	**30**	**0**	**0**	**1**	**1**	**1**	**0**	**0**	**1**	**0**	**0**	**0**	
Abs. δ	-0.10	0.05	0.13	-1.18	0.03	0.06	0.03	0.12	0.02	-0.02	-0.01	-0.01	0.87	
Rel. δ %	**-17**	**12**	**2**	**-5**	**11**	**65**	**4**	**8**	**7**	**-56**	**-68**	**0**	**1**	

4.5.2 Reflected Light Microscopy

4.5.2.1 The principle

Any modern research optical microscope will consist of the same main parts: first of all, illuminators as sources of light. These are critically necessary for mineral identification, because the colour of a mineral is the colour of light unabsorbed on transmission or reflection (see Nesse 2004: 10). Although I used a dual research purpose microscope, Leica DM-LM model, with a base illuminator for transmitted light and vertical illuminator for reflected light, my optical analysis of the polished (blocks) sections was carried out using the reflected light system, because most of slag minerals are opaque (e.g. Ineson 1989; Gribble and Hall 1992; Nesse 2004; Joosten 2004). The principle is understood; a (polarized) incident beam falling on the polished surface reflects specific properties of the opaque minerals (see Joosten 2004: 35). Second, the analyzers and polarisers equipped with polarizing films for light polarization (Gribble and Hall 1992: 2).When the analyser is taken out of the light path gives a plane polarized light image (PPL) with a bright field of view, but it gives a crossed polarized light (XPL) with a dark field of view when inserted in the light path (see Gribble and Hall 1992: 18). For the purpose of careful identification of the minerals in the slags, I concentrated on PPL techniques. Third, objective lenses for image magnification. Fourth, a flat and rotatable stage for holding samples or slides. Lastly, the oculars (eyepieces) for focusing and further magnification of the objective lens image between 5 and 12 times (see Nesse 2004: 19), although our microscope has binoculars with 10 times magnification. This means that total magnification of the images seen under the microscope is equal to the magnification of the objective lens times the magnification of the oculars.

4.5.2.2 Preparation of polished blocks

Sample preparation included:

(1) cutting the sample,

(2) drying the sample,

(3) preparation of labels and resin,

(4) setting the sample in the resin,

(5) grinding, and

(6) polishing stages.

A small piece from each of the (XRF) slag samples was cut gently using the abrasive diamond tile cutter and let to dry on an electric drier. An epoxy resin was mixed with a hardener to a ratio of 4:1. The specimen was mounted into the resin at the centre of a green sample cup, with the side to polish facing downwards, and the label gently placed to the inside wall of the cup while the letters upside down. The resin was left to harden and produce blocks overnight.

The blocks were removed from the cups, ground using the Buehler MetaServ hand grinder with water and P120, P320, P600, and P1200 grit numbers equivalent to approximately 127, 46, 25, 15 µm respectively. The blocks with a 3 cm diameter were resized using the cutter to 1 cm thick, and were cleaned for polishing. An automatic Buehler MetaServ 3000 grinder-polisher with a vector LC power head was used to polish the blocks at approximately 8 and 5 µm using water and silicon carbide abrasive paper discs. Final polishing at 1 and 0.25 µm cloths was done using an automatic Struers LaboPol-5 polisher with Buehler MetaDi II diamond paste and diamond lubricant water. Speed for the polishers was set up at 150 rpm and blocks were cleaned using industrial methylated spirit (IMS) between each polishing stage, and an optical microscope aided to monitor the progress of each of the polishing stage in terms of the

decreasing scratches. It is noteworthy that sample blocks rich in magnetite minerals were hard to polish using the diamond paste procedure as described above. Instead, an alumina suspension was used for final polishing at 5 and 1 µm respectively. While the former procedure took 3-6 minutes to get to the next polishing stage, the latter took up to two hours. Final polishing was followed by a deep cleaning of the sample blocks in the ultrasonic bath with IMS for 20-30 minutes, drying at the electric drier for 10-20 minutes, and packed into plastic sample boxes for examination.

4.5.2.3 Analysis

I started by adjusting the camera zoom of the microscope for accurate measurements of the field of view (FoV) and mineral sizes. To this end, I focussed the micrometer scale on the stage, and set it up to 1 mm equals to FoV at *x*100 magnification, and a photo of the scale taken (Figure 4.18). The microscope was set at this magnification, because it was convenient to take images at lower (*x*50) and higher magnifications (*x*200, *x*500). Based on the scale set up, the FoV at *x*50, *x*200, and *x*500 magnification was 2 mm, 0.5 mm, and 0.2 mm respectively. Most of the images were photographed at *x*100 magnification for cross-sample comparison, because the increase in magnification of the images simultaneously reduced the focus of the images.

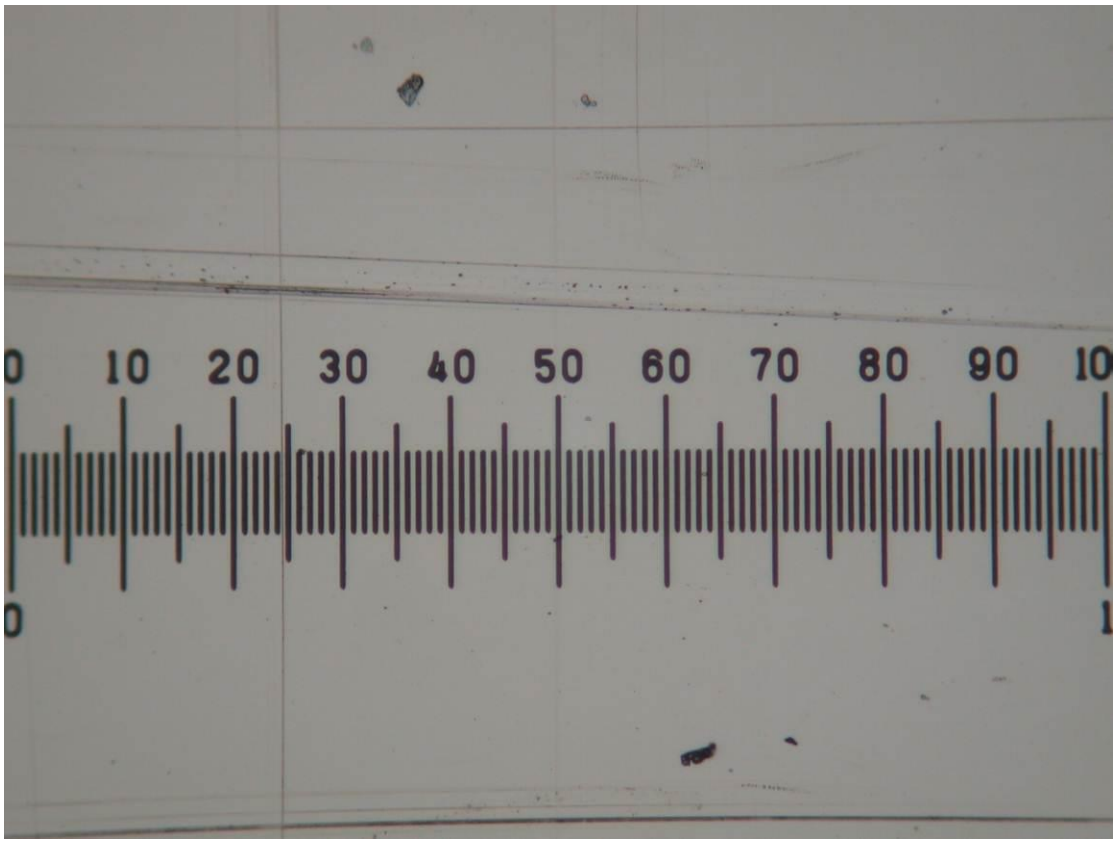

Figure 4.18: PPL photomicrograph of 1 mm FoV scale at *x*100 magnification

The analysis itself focussed on the observation of the slag microstructure. The crystal shape, colour, polishing hardness, the approximate concentration and distribution of some phases such as wüstite, magnetite, and haematite are used as a guide to the technical efficiency and operating parameters. To examine the first two properties, crystal shape and colour, I relied much on previous experiences as Nesse (2004: 125) puts it, "proficiency in identification of minerals with a standard RLM depends on gaining experience based on having looked at many samples". From experience and written sources, an optical properties guiding table was developed for the identification of the iron slag minerals on RLM (Table 4.8). In addition, magnetite regularly exhibited hard polishing properties (e.g. Nesse 2004: 111), and in particular, the refining slags samples from Ufipa and Unyiha, and smelting slags samples from Mbinga consistently showed up iron droplets. The iron droplets were etched by nital, in order to reveal any

possible iron microstructures, but examination was difficult given the small size of the metallic droplets *circa* 80 microns. Some of the identified phases under RLM technique were finally confirmed by scanning electron microscopy (SEM-EDS) compositional examination, and the elemental analysis of the metallic droplets was done by electron probe micro-analyser (EPMA) (see electron microscopy below).

Table 4.8: Optical properties of the iron slag minerals on plane polarized RLM

Phase	Shape	Colour	Remarks
Haematite	trigonal, hexagonal	grey to white	see Ineson 1989: 117; Gribble and Hall 1992: 179
Magnetite	angular, cubic	grey to white grey	see Ineson 1989: 121; Gribble and Hall 1992: 182
Wüstite	round egg-like, dendrites	white grey	see Anthony *et al*. 1997: 608
Iron, steel	angular, cubic, droplets	white	see Anthony *et al*. 1990: 241
Fayalite	skeletal, elongated	dark grey	see Nesse 2004: 241
Hercynite	angular, cubic	darker than fayalite	see Anthony *et al*. 1997: 243
Ulvite	angular, cubic	brownish grey, to reddish	see Gribble and Hall 1989: 182; Anthony *et al*. 1997: 582
Glass	amorphous matrix	black	http://en.wikipedia.org/wiki/Glass
Leucite	equant trapezohedral, tetragonal, pseudocubic	dark grey	see Anthony et al. 1995b: 462; Nesse 2004: 154
Zirconia	small angular	white	http://en.wikipedia.org/wiki/Zirconium_dioxide
Ilmenite	trigonal, hexagonal	brownish, pinkish	see Ineson 1989: 119; Gribble and Hall 1992: 180
Quartz	hexagonal, trigonal	dark grey	see Nesse 2004: 129
Porosity	amorphous, circles	black	

4.5.3 Electron Microscopy

4.5.3.1 The principle

Electron microscopes are based on the use of an electron beam to create inner electron shell vacancies in the sample surfaces, and thus stimulate X-ray emission (e.g. Pollard and Heron 2008: 46; Henderson 2000: 17). The primary beam of electrons is produced in a conventional electron gun, where a heated cathode, maintained at ground potential, emits electrons extracted through a positive potential into the focussing elements of the microscope (see also Pollard *et al*. 2007: 109; Pollard and Heron 2008: 46). While the electron beam strikes the sample two types of energy are released. The first is a very low energy secondary electrons (SE) that escape and can be detected from the top few atomic layers of the sample, which make them sensitive to morphology and surface topography of the sample, and the basis for image formation process in electron microscopes (Pollard *et al*. 2007: 109). The second are high energy backscattered electrons (BSE) that escape from deeper within the sample. Because the intensity of the BSE is proportional to the atomic weight of the nuclei, the intensity variation across the surface will be proportional to the average atomic number of the surface, which eventually gives a BSE image with useful structural data; (3) some incident electrons will create inner shell vacancies that can de-excite through the emission of characteristic X-rays, making it the basis of the analytical operation of the electron probe micro-analyser (EPMA) (e.g. Pollard *et al*. 2007: 109; Pollard and Heron 2008: 47). There are five electron microscopes at the UCL Institute of Archaeology, with energy dispersive (SEM-ED) spectrometer, and/or wavelength dispersive (SEM-WD) spectrometers. The former provide high quality images and simultaneous multi-element analysis, while the latter (also referred to as electron probe micro-analyser (EPMA), see Henderson 2000: 18; Pollard and Heron 2008: 48) is used sparingly for analytical purposes. In terms of

detection limits, the SEM-EDS has considerably higher limits of detection than the EPMA for all elements, typically by one or two orders of magnitude (see Pollard and Heron 2008: 48). Also, electrons are focussed at a point with the EPMA, but they are focussed on a particular plane with the SEM-EDS (see Henderson 2000: 18). For the purpose of this work, SEM-EDS was used for production of quality images, and slag area and phase analysis, while the EPMA was primarily employed to examine the elemental composition of the iron droplets in the slags from Sumbawanga, Mbozi, and Mbinga (see Chapters 5-7).

4.5.3.2 Analysis on the SEM-EDS

All samples were carbon-coated to make them conductive. One sample and a cobalt standard were placed in the chamber of a Hitachi S-3400N SEM machine with an EDS for the analysis. The machine was calibrated using the cobalt standard for reliable quantitative results, and working conditions were set at acceleration voltage 20 kV, working distance (distance between the sample and detector) 10 mm, probe current *circa* 0.5-1 nA and deadtime 30-40 %. Images were captured using the BSE detector, bulk area analysis at *x*50 magnification, and semi-bulk chemical area analysis at *x*200 magnification as well as the point analysis were undertaken. In the course of the analysis, and at the end of the analysis of every sample, *circa* 1-1.5 hour period, the machine was recalibrated using the cobalt standard, with a view to check its reliability and stability. The quantitative results were reported as oxides by stoichiometry using a built-in INCA software, and normalised to 100 wt% to account for the porosity of the slags, instability of the machine, and for the purpose of comparing with other published and unpublished data.

4.5.3.3 SEM-EDS data quality assessment

Three RMs, namely, BCR-2 Basalt Columbia River, BIR-1 Icelandic Basalt, and BHVO-2 Basalt Hawaiian Volcanic Observatory (see Appendix 4.5a-c) were analysed, in order to assess the precision and accuracy of the machine. Tables 9 through 11 (Table 4.9, Table 4.10, Table 4.11) present the results of the assessment of the 3 RMs. The precision of the data was very good, well below 8% confidence interval, although as an exception, precision for MnO in the BCR-2 was poorer (see Table 4.9), possibly because of its lowest concentration of *circa* 0.1 % being very close to the detection limit of the SEM-EDS machine. Also, the accuracy was very good for all oxides of the 3 RMs, with relative errors of below 10 % on average, and in many cases below 5%. On the basis of the very good precision and accuracy results of the machine, there is no reason to doubt the quality of the real sample data generated by the machine and presented in Chapters 5-9.

Table 4.9: Normalised data quality assessment for the BCR-2 standard

BCR-2	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	FeO
Measurements	%	%	%	%	%	%	%	%	%
Area 1	3.1	3.4	12.5	56.5	1.9	7.3	2.4	0.3	12.7
Area 2	3.0	3.4	12.7	56.5	1.8	7.3	2.4	0.1	12.6
Area 3	2.8	3.4	12.7	56.8	1.9	7.3	2.4	0.2	12.4
MV	3.0	3.4	12.6	56.6	1.9	7.3	2.4	0.2	12.6
CV	3.2	3.6	13.5	54.1	1.8	7.1	2.3	0.2	12.4
SD	0.2	0.0	0.1	0.2	0.1	0.0	0.0	0.1	0.1
CoV %	**6**	**0**	**1**	**0**	**3**	**1**	**1**	**51**	**1**
Abs. δ	-0.2	-0.2	-0.9	2.5	0.1	0.2	0.1	0.0	0.2
Rel. δ %	***-6***	***-5***	***-6***	***5***	***5***	***3***	***5***	***7***	***1***

Table 4.10: Normalised data quality assessment for the BIR-1 standard

BIR-1	Na_2O	MgO	Al_2O_3	SiO_2	CaO	TiO_2	FeO
Measurements	%	%	%	%	%	%	%
Area 1	1.6	9.4	14.7	49.5	13.4	1.1	10.1
Area 2	1.7	9.4	14.3	49.8	13.7	1.0	10.1
Area 3	1.6	9.3	14.3	49.7	13.8	1.1	10.3
MV	1.6	9.3	14.5	49.7	13.6	1.1	10.2
CV	1.8	9.7	15.5	48.0	13.3	1.0	10.2
SD	0.1	0.1	0.2	0.1	0.2	0.0	0.1
CoV %	**4**	**1**	**2**	**0**	**1**	**4**	**1**
Abs. δ	-0.2	-0.4	-1.0	1.7	0.3	0.1	0.0
Rel. δ %	***-10***	***-4***	***-7***	***4***	***3***	***13***	***0***

Table 4.11: Normalised data quality assessment for the BHVO-2 standard

BHVO-2	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	FeO
Measurements	%	%	%	%	%	%	%	%
Area 1	2.0	6.8	12.6	52.1	0.6	11.5	2.9	11.5
Area 2	1.8	7.1	12.5	51.9	0.5	12.1	3.0	11.1
Area 3	2.2	6.7	12.5	51.7	0.5	11.8	3.2	11.4
MV	2.0	6.9	12.6	51.9	0.5	11.8	3.0	11.3
CV	2.2	7.2	13.5	49.9	0.5	11.4	2.7	11.1
SD	0.2	0.2	0.06	0.2	0.04	0.3	0.2	0.2
CoV %	**8**	**3**	**0**	**0**	**7**	**3**	**5**	**2**
Abs. δ	-0.2	-0.4	-1.0	2	0.02	0.4	0.3	0.2
Rel. δ %	***-10***	***-5***	***-7***	***4***	***4***	***3***	***11***	***2***

4.5.3.4 Analysis on the EPMA

A JEOL JXA-8100 superprobe was used for microanalysis of the slag metallic droplets. Three polished block samples and one block of 5 standards (SS 431-5 Plain Carbon Steels), to produce a calibration curve, were gold-coated (thin gold coating) at the same time in the Quorum Q150R ES machine, in order to match the gold-coat thickness for good equal rate of X-rays absorption. The standardisation process was unique to each batch of samples and control materials. Because I wanted to quantify carbon in the iron droplets, I was keen to avoid any carbon contamination. To this end, I deliberately used

a liquid nitrogen *cold finger* technique to fully remove or rather condense any 'system-carbon' in the chamber due to the use of oil pump for the vacuum system. Also, a calibration curve (Figure 4.19) was used to measure carbon as opposed to the ZAF model. Lastly, the machine was set at a 10 kV acceleration voltage, and probe current of *circa* 15 nA for the carbon area analysis. Calibration of the machine using the standards was re-done after the analysis of every three samples.

After the carbon (and iron) microanalysis, the gold-coat was polished off, and the samples were carbon-coated, in order to measure elements other than carbon present in the iron droplets. For this procedure, the machine was set at a 20 kV acceleration voltage, probe current of 50 nA, and the ZAF model was used to measure the concentration of the elements on the same areas of the iron droplets. The results for both procedures were reported as elements, and were normalised to 100 wt% to allow comparison with the published data.

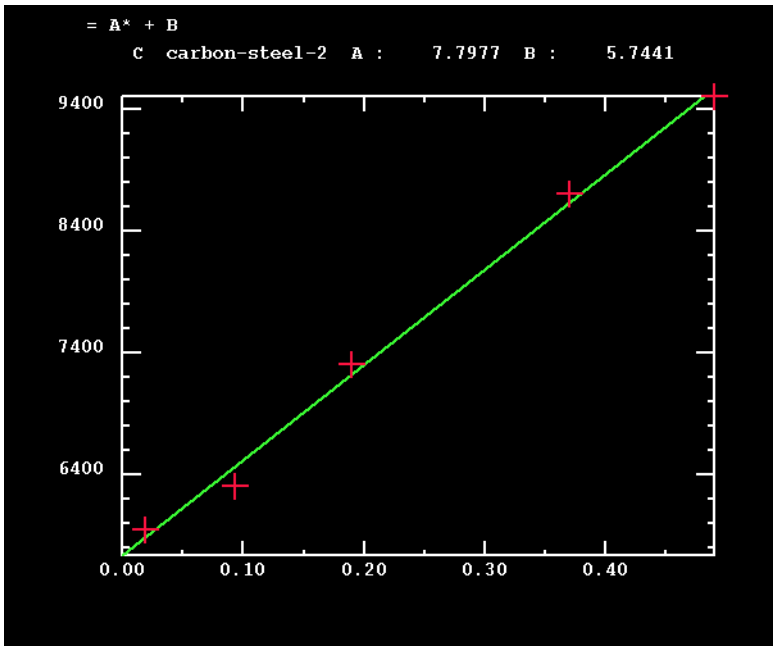

Figure 4.19: Carbon quantification calibration curve of the 5 Plain Carbon Steel standards with even distribution of carbon. Note that the vertical axis = counts/second, and horizontal axis = carbon concentration; total counts/element=100 seconds

4.5.3.5 EPMA data quality assessment

The BAS 1/19 Low Phosphorous Iron reference material (see Appendix 4.6) was measured, and its results were compared to the published data, in order to assess the precision and accuracy of the machine, and the resultant data. Table 4.12 presents the results of the assessment of the RM. The precision was very good on measuring silicon, copper, nickel, iron, and carbon, and was bad for the rest of the elements. Also, the accuracy was very good for silicon, copper, nickel, iron, and carbon, in addition to phosphorous, molybdenum, and tin. The rest of the elements were under-represented by the machine, and for the purpose of quality data, they have been ignored in the real sample data (see Chapters 5-7).

Table 4.12: Normalised data quality assessment for the BAS-LPI 1/19 standard

BAS-LPI 1/19	Si	P	Al	Cu	Mo	Ni	S	Sn	Mn	Cr	Fe	C	AT
Measurements	%	%	%	%	%	%	%	%	%	%	%	%	%
Area 1	2.32	0.02	0.01	0.45	0.20	0.17	0.01	0.03	0.36	0.62	92.78	3.04	100.40
Area 2	3.22	0.07	0.00	0.53	0.36	0.20	0.01	0.05	0.31	0.39	91.86	2.99	101.65
Area 3	2.81	0.02	0.01	0.54	0.15	0.20	0.00	0.02	0.31	0.42	92.49	3.01	101.19
Area 4	2.71	0.04	0.01	0.52	0.23	0.21	0.01	0.04	0.00	0.00	93.13	3.10	98.79
Area 5	2.80	0.04	0.00	0.55	0.24	0.20	0.01	0.04	0.34	0.46	92.32	3.00	100.89
Area 6	2.67	0.02	0.00	0.50	0.22	0.18	0.00	0.04	0.31	0.50	92.49	3.07	100.45
Area 7	2.45	0.02	0.00	0.40	0.26	0.17	0.01	0.03	0.35	0.69	92.50	3.13	99.45
Area 8	2.86	0.07	0.00	0.44	0.42	0.17	0.00	0.05	0.02	0.01	92.73	3.23	99.66
Area 9	2.68	0.06	0.01	0.47	0.37	0.18	0.00	0.05	0.35	0.58	92.22	3.02	100.00
Area 10	2.79	0.13	0.04	0.42	0.72	0.15	0.26	0.09	0.85	0.56	90.93	3.07	100.45
MV	2.73	0.05	0.01	0.48	0.32	0.18	0.03	0.04	0.32	0.42	92.34	3.07	100.29
CV	2.8	0.05	0.02	0.47	0.33	0.19	0.07	0.05	0.44	0.5	91.94	3.1	99.96
SD	0.24	0.04	0.01	0.05	0.16	0.02	0.08	0.02	0.23	0.24	0.60	0.07	
CoV %	**9**	**73**	**144**	**11**	**52**	**10**	**261**	**41**	**72**	**56**	**1**	**2**	
Abs. δ	-0.07	0.00	-0.01	0.01	-0.01	-0.01	-0.04	-0.01	-0.12	-0.08	0.40	-0.03	
Rel. δ %	***-2***	***-2***	***-55***	***3***	***-4***	***-4***	***-56***	***-11***	***-27***	***-15***	***0***	***-1***	

4.6 Summary

This chapter has examined the reasons for the application of the different field and laboratory methods for data collection and analysis. Most of the field data were surface collections, and hence collected via surface walk-over surveys, and that excavations were carried out to retrieve older materials, for the purpose of comparing ancient and recent (for the relative chronology of the study sites, see Appendix 4.7) iron and steel production techniques. Initial phase of microscopic analysis was done via optical microscopy, and the verification of the phases was done through electron microscopy. Quantitative data were produced by XRF and electron microscopy analytical techniques. The quality of the quantitative data has been critically assessed, in order to justify their significance in explaining the research problem, and particularly, in addressing the specific research objectives for this work. The following chapter presents macroscopic and microscopic data from Sumbawanga.

5. Iron and High Carbon Steel Production in Sumbawanga

5.1 Preamble

This chapter focuses on iron smelting and refining processes in Sumbawanga district (Figure 5.1) of the Rukwa region. The land is generally referred to as Ufipa, because the majority of the indigenous people are Fipa (LOT 2009: 94). The name Fipa comes from the word 'lyamfipa', meaning people who live on a plateau (Wembah-Rashid 1969: 65). The chapter starts by the presentation and interpretation of new macroscopic and microscopic data. Secondly, the data are then discussed in relation to the aims of the chapter. Finally, the summary provides the synthesis that ironworking in Ufipa was a three-stage process, including the *vintengwe* process situated between smelting and primary and secondary smithing processes, and one that technically aimed at the production of carbon-rich steel, *not* soft iron as previously thought.

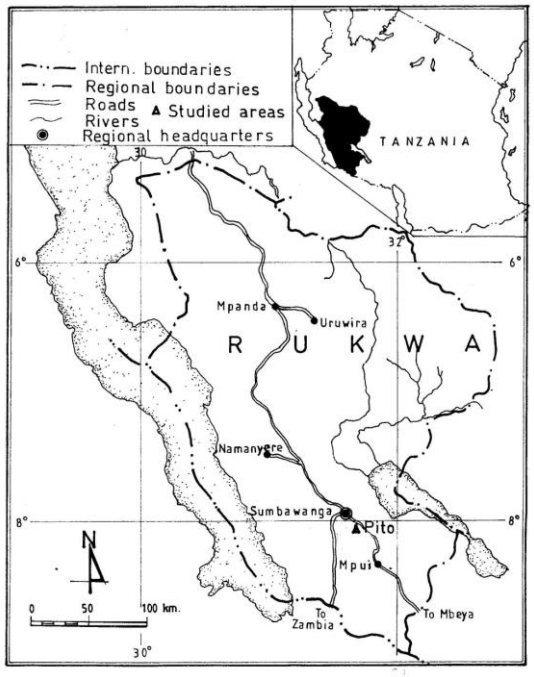

Figure 5.1: Map of the Rukwa region showing location of Sumbawanga and Pito ward

5.2 Presentation and Interpretation of Macroscopic Data

5.2.1 Sites: Location, Size, Preservation, and Context of the Material

5.2.1.1 Location

The fieldwork was conducted in six sub-villages, namely Mkumbi, Chulu, Kamafupa, Nangesu, Nantula, and Tupa in Pito ward (Figure 5.2) located about 15 km south east of Sumbawanga municipal centre (see Figure 5.1). From these sub-villages I have discovered and recorded 121 sites including 72 smelting, 45 refining, two smithing sites as well as two ore mining sites (see Appendix 5.1 through 5.6). Based on GPS readings, the sites are located between latitude S (8^{o} 4' and 8^{o} 7') and longitude E (31^{o} 38' and 31^{o} 42') *circa* between 1880 and 1960 m above mean sea level. Although both smelting and refining sites are often located close to ore sites, water sources within 200 m, and next to termite mounds, smelting sites are always located on the western side of termite mounds (see also Greig 1937; Wise 1958; Barndon 1992; Mapunda 1995a, 1995b, 2010).

Figure 5.2: Map of Pito ward showing the location of the studied sub-villages and the number of the sites per village

5.2.1.2 Area Size

The area data (see Appendix 5.1 through 5.6) was determined by πr^2 (π=pie, r= radius) formula. Based on the data, it is clear that the smelting sites are generally larger than the refining sites, because the former are about 330 m^2, and the latter are about 220 m^2 in area size. The general and relative difference in area size (and in volume of the materials) is unsurprising information, because the smelting furnaces consumed more bulk raw materials including iron ores and charcoal than the small refining furnaces,

which were charged with (impure) iron and charcoal alone (e.g. Greig 1937: 79; Wise 1958: 110; Mapunda 1995a: 50), let alone the fact that *malungu* were larger than *vintengwe* furnaces. For the same reason, the smithing sites are the smallest in terms of area size, measuring about 79 m^2 on average.

5.2.1.3 Preservation

Good preservation of the sites, among other things, is indicated by the presence of still standing *malungu* furnaces in these sub-villages. Generally all the sites in Pito ward are well preserved. The Mkumbi and Chulu sites are not presently located in people's farms, and this has largely helped their preservation. Some of the Kamafupa and Tupa sites are not located in farms, and as a result, they are well preserved as well. Surprisingly, even those located in farms including the Nangesu and Nantula sites are undisturbed and remain isolated clusters, probably because it is difficult to cultivate such as areas with (block) slags. The recent pot and hearth (Figure 5.3) discovered at Kamafupa SE13 are perhaps part of the smelting medicine legacy, because today smelting sites in Ufipa function as ritual or rather sacred places (see also Mapunda 2010). In addition to this conservation advantage, I conducted two public archaeology talks (Figure 5.4) to raise awareness in the community of the importance of such cultural heritage for socio-economic development of Sumbawanga as well.

Figure 5.3: Recent ritualistic pot (left) and cooking hearth (right) from Kamafupa SE13

Figure 5.4: Participants of the public archaeology talk in Sumbawanga municipal council

5.2.2 Context of the Materials

The collected materials including slags, tuyères, and furnace walls were basically surface collections, although two smelting and six refining debris heaps from Mkumbi sites, for example, were excavated to learn the exact material composition, weight, and

volume of the heaps (Table 5.1). In addition, clay blocks made from respective termite mounds were shipped to London for firing and chemical analyses.

Table 5.1: Excavated materials from smelting (SE) and refining (RF) sites at Mkumbi area. SE volume= 400-3,000 Litres, and RF volume= 80-270 Litres. Note average=total quantity (#) or weight divided by number of sites

S/No.	Site	Furnace Walls		Tuyères		Slags		Blooms		Remarks (important inclusions)
		#	Wt (kg)	#	Wt (kg)	#	Wt (kg)	#	Wt (kg)	
1	SE3	42	8	332	35	73000	1945	?		Blocks, tuyère-moulds, multiple tuyères
2	SE4	72	15	1240	70	110640	6210	?		Blocky slags, tuyère-moulds, multiple tuyères
3	RF2	6	1	30	3	7503	7503	4	0.5	8 droplet slags, smooth slags
4	RF5A	8	2	110	5	29376	489	4	0.25	Also, consisted of 1 cake, 7 droplets, smooth slags
5	RF6	8	0.5	8	2	8172	337	6	0.5	Also, consisted of 1 cake, 5 droplets, smooth slags
6	RF8	3	0.5	67	2	5304	180	6	0.5	5 droplets, smooth slags
7	RF9	8	2	45	3	10164	109	5	0.25	4 cakes, smooth slags
8	RF13A	6	0.5	61	6	9108	414	4	0.5	4 complete tuyères, 4 cakes, smooth slags
9	**Average (SE)**	**57**	**12**	**786**	**53**	**91820**	**4078**			
10	**Average (RF)**	**7**	**1**	**54**	**4**	**11605**	**1505**	**5**	**0.5**	

5.2.3 Furnace Attributes

5.2.3.1 *Malungu* smelting furnaces

Based on the dimensions of complete furnaces (see Table 5.2), Fipa smelting furnaces are tall shaft superstructures *circa* 3 m in height, meant to serve several smelting seasons. They are larger in diameter at the base, relatively small in the middle, and even smaller at the top (Figure 5.5). Also, the wall thickness decreases with height, thicker at the base and relatively smaller at the top. According to oral evidence, the concentric rings on the walls represent the courses of construction of the furnaces (see also Mapunda 2010: 152). At 100-125 cm high, opposite *palinyina*, a peep hole was made to monitor progress in the furnace. Furthermore, they have shallow pits of about 8-15 cm deep, based on excavation of the furnaces' inside. To sum up and in terms of these attributes, the Pito *malungu* furnaces are generally and relatively similar to both the *malungu* furnaces recorded elsewhere in Ufipa (e.g. Greig 1937; Wembah-Rashid 1969; Barndon 2004; Mapunda 2010) and *malungu* furnaces of Unyiha (Brock and Brock 1965; Lyaya 2010; Ngonadi 2010).

Table 5.2: Dimensions of iron smelting furnaces from Pito ward sites. Note E=external, I=internal, B=base, M=middle, T=top, D=diameter, WT=wall thickness

S/No.	Site	External Diameters (m)			Internal Diameters (m)			Wall thickness (cm)			Height (m)	# of Ports
		EBD	EMD	ETD	IBD	IMD	ITD	BWT	MWT	TWT		
Smelting furnaces from Kamafupa												
1	SE2	1.9	?	?	1.45	?		22	?	?	1	9
2	SE10	1.95	1.7	1.175	1.54	1.34	0.875	20	18	15	2.75	10
3	SE15	1.85	1.7	1.16	1.45	1.3	0.92	20	20	12	2.7	
Smelting furnace from Chulu												
4	SE7	2.3	?	?	1.7	?		30	?	?	0.7	11
Smelting furnaces from Tupa												
5	SE18	2.2	?	?	1.72	?		24	?	?	0.9	9
6	SE28	2.38	2	1.19	1.98	1.7	0.93	20	15	13	3.25	11
7	**Average**	**2.1**	**1.8**	**1.2**	**1.6**	**1.4**		**23**	**18**	**13**	**3**	**10**
8	**SD**	**0.2**	**0.2**	**0.0**	**0.2**	**0.2**	**0.03**	**3.9**	**2.5**	**1.5**	**1**	**1**

Figure 5.5: Smelting *ilungu* furnace from Kamafupa in Pito, southern Ufipa

5.2.3.2 *Vintengwe* refining furnaces

Although a considerable number of refining sites with slags, tuyères, blooms, and furnace walls were discovered, this project did not discover standing *vintengwe* furnaces (see also Davison and Mosley 1988: 61). I was told by my informants (see Appendix 4.2a) that these furnaces were often meant not to last as the *malungu* furnaces did. For the details of the height, size, and diameters of the *vintengwe* furnaces, the reader is referred to Chapter 2 (Previous Archaeological Knowledge in Sumbawanga) and Chapter 3 (*Malungu* Ore Smelting and *Vintengwe* Iron Refining Processes) sections.

5.2.4 Tuyère Ports and Tuyeres

5.2.4.1 *Malungu* tuyère ports and tuyères per port

On average, *malungu* furnaces had ten tuyère ports including *palinyina* (Figure 5.6; see also Mapunda 2010: 153). The ordinary ports measured about 10-15 cm wide and 25-35 cm high, while the *palinyina* were about 32-50 cm wide and 35-45 cm high. The former ports were less wide for technical reasons: 3-4 tuyères (Figure 5.7) were inserted horizontally, one on top of the other in one port, as opposed to relatively wider tuyère ports in Umatengo (see Chapter 7) in which multiple tuyères were inserted horizontally, one besides the other (see Kapinga 1990). For the same reason, the *palinyina* were wider, because they were equipped with about 6-12 tuyères (2 or 3 more tuyère columns), and at the end of the smelting episodes were used as the mother doors or rake holes as well.

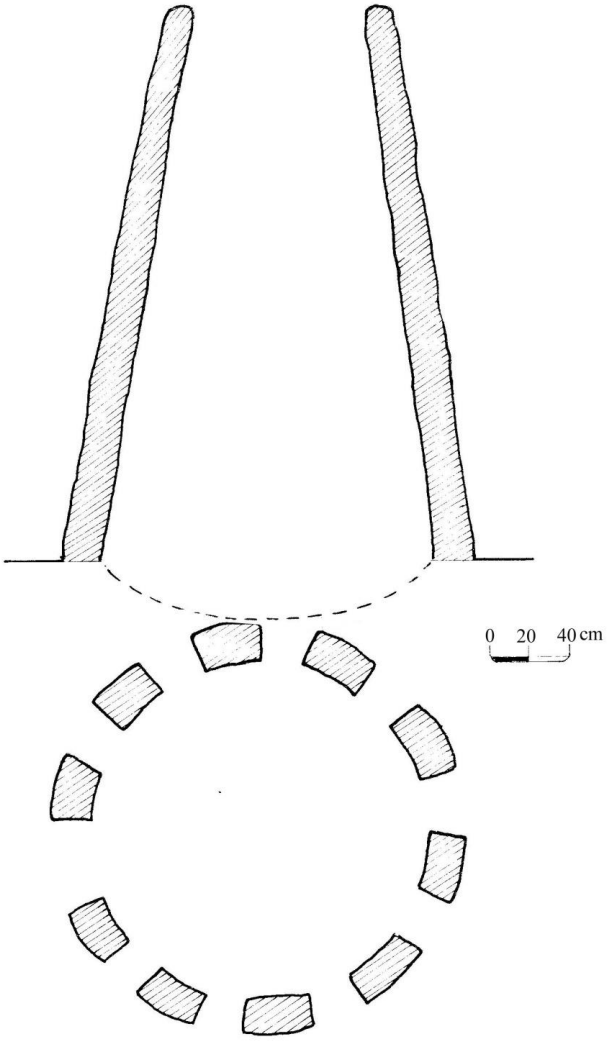

Figure 5.6: Sketch of the tuyère ports of *malungu* in Pito, southern Ufipa

Figure 5.7: Multiple tuyères from smelting sites in Pito, southern Ufipa

5.2.4.2 *Vintengwe* tuyère ports and tuyères per port

I was told by the informants (see Appendix 4.2a) that the *Vintengwe* furnaces had three tuyère ports, with one tuyère per port, and there was the fourth tunnel that was used for slag tapping (see also Greig 1937: 79). Because of the rarity and fragmentary nature of the *vintengwe* (Mapunda 1995b, 2010), hitherto we do not know the exact sizes of the ports. Nevertheless, because each housed only one tuyère, they should have been considerably smaller and less wide than the *malungu* tuyère ports (Figure 5.8).

Figure 5.8: *Kintengwe* iron refining furnace in Ufipa (Source: Barndon 2004: 4). Note two of the grandsons of Mzee Stephano Malimbo, master smelter in Ufipa (see Wright 2002)

5.2.4.3 *Malungu* and *vintengwe* tuyère attributes

Some of the tuyères were bloated at distal ends, suggestive of exposure to high temperatures close to maximum tolerance (Freestone and Tite 1986). Both smelting and refining tuyères had no flared proximal ends. Although unflared tuyères are conventionally associated with smelting by natural draft mechanism (e.g. Mapunda 2010), it is understood from the oral evidence (see Appendix 4.2a) that the Fipa smelters exceptionally connected bellows to unflared proximal ends of the tuyères for the refining process. The latter information is vital to alert archaeologists not to entirely rely on the flared proximal end evidence alone, but they should also envisage other factors such as number of tuyère ports and the size of the furnaces (see van der Merwe and Avery 1987: 149) when dealing with furnace air supply mechanism.

Furthermore, the *malungu* tuyères are similar to the *vintengwe* tuyères in diameter and thickness (Table 5.3). The similarity in diameter can be explained, because respondents asserted that both types were manufactured using the same smooth tree stick called *untalembe* (elsewhere see Klapwijk 1986b). Also, using a thread, the *vintengwe* tuyères were made shorter than the *malungu* tuyères, because of the relative small size of the *vintengwe* furnaces. The diameter of the tuyères is generally smaller than the diameter of the Kigonsera (see Chapter 7) and Njombe (see Chapter 9) (flared) tuyères. Lastly and in addition to the difference in lengths, the smelting tuyères frequently have slag clogging, while the refining tuyères do not (for possible reasons, see slag sub-section below).

Table 5.3: Macroscopic attributes of the tuyères from Pito ward smelting (SE) and refining (RF) sites. Note E=external, I=internal, and D=diameter. Note each of the dimensions represents the average of five measurements of (similar) tuyères

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Segment	Remarks
Smelting tuyères from Pito						
1	Mkumbi SE6	6	2.3	1.9	body	
2	Mkumbi SE6	5.8	2.4	1.7	body	
3	Chulu SE7	6	2.5	1.8	body	
4	Chulu SE7	5.9	2.5	1.7	body	
5	Kamafupa SE11	6.1	2.4	1.9	proximal	unflared
6	Kamafupa SE11	5.9	2.5	1.7	proximal	unflared
7	Nangesu SE12	5.8	2.4	1.7	distal	
8	Nangesu SE12	5.9	2.4	1.8	distal	
9	Tupa SE28	6	2.5	1.8	distal	bloated
10	Tupa SE28	6.3	2.4	2.0	body	
11	Nantula SE1	6	2.3	1.9	body	
12	Nantula SE1	5.9	2.6	1.7	distal	bloated
Refining tuyères from Pito						
13	Mkumbi RF5A	5.7	2.3	1.7	complete	Unflared
14	Mkumbi RF5A	5.8	2.4	1.7	complete	Unflared
15	Mkumbi RF13A	5.9	2.5	1.7	complete	Unflared
16	Mkumbi RF13A	6	2.4	1.8	complete	Unflared
17	Kamafupa RF8	6	2.4	1.8	distal	
18	Kamafupa RF8	6.2	2.3	2.0	distal	bloated
19	Kamafupa RF9	6.1	2.4	1.9	body	
20	Kamafupa RF9	5.9	2.4	1.8	body	
21	Tupa RF8	6	2.3	1.9	distal	
22	Tupa RF8	5.8	2.4	1.7	distal	bloated
23	Tupa RF51	6.1	2.5	1.8	body	
24	Tupa RF51	6	2.5	1.8	proximal	Unflared
25	**Average (SE)**	**6.0**	**2.4**	**1.8**		
26	**Average (RF)**	**6.0**	**2.4**	**1.8**		

5.2.5 Slag Attributes

For the sake of comparison though depending on how the slag cooled, smelting and refining slags are classified into two or three categories. These are cake-like slags

(solidified inside the furnaces), tap or flow slags (cooled outside the furnaces), and tuyère-mould slags (cooled inside the tuyères while being tapped; see Chapter 2, subsection 2.3.1). The morphology of smithing slags is presented at the end of this sub-section.

5.2.5.1 Smelting and refining cake-like slags

Table 5.4 indicates that the cake-like slags from the *malungu* are relatively heavier than the cake-like slags from the *vintengwe* process. On average, the former weigh about 7 kg, while the latter weigh about 1.25 kg. Also, the smelting cake-like slags (Figure 5.9) are relatively larger in size than the refining cake-like slags (Figure 5.10). The difference in weight and size, it can be argued, is more probably the function of the differences in the size and nature of the charge of the respective furnaces. Despite the differences, cake-like slags were relatively more magnetic on bar and pencil magnets than tap slags (see below), have rough surfaces, reddish or yellowish, and sometimes impregnate some charcoal pieces. They are magnetic, probably because they were close to highly magnetic iron and steel respectively as final products (see Mapunda 2010).

Table 5.4: Macroscopic attributes of the smelting (SE) and refining (RF) cake-like slags from Pito, southern Ufipa. Note each of the dimensions represents the average of five measurements of (similar) slags. Note SD=standard deviation

S/No.	Site	Mass (kg)	Length (cm)	Width (cm)	Thickness (cm)
Smelting cake-like slags					
1	Mkumbi SE11	11	40	30	15
2	Mkumbi SE12	7	34	30	14
3	Mkumbi SE12	5	26	23	14
4	Nangesu SE6	3.5	25	20	11
5	Nangesu SE8	5	27	20	11
6	Kamafupa SE2	9	50	25	11
7	Kamafupa SE2	9	45	23	13
8	Tupa SE39	7	35	25	10
9	Tupa SE40	4.5	22	18	10
10	Tupa SE40	7	55	35	11
11	Nantula SE8	8	48	28	10
12	Nantula SE10	8	42	19	10
Refining cake-like slags					
13	Mkumbi RF13A	1.5	15	9	7
14	Mkumbi RF13A	1	8	6	5
15	Mkumbi RF13A	2	10	6	5
16	Mkumbi RF2	1	12	7	4
17	Mkumbi RF2	1	7	4	3
18	Mkumbi RF2	0.8	6	5	2
19	Kamafupa RF4	1.2	7	5	3
20	Kamafupa RF4	1.3	5	4	2
21	Tupa RF51	2	8	4	2
22	Tupa RF51	1.2	7	5	3
23	Tupa RF51	1.5	7	6	4
24	MLBRF9	1.5	15	8	5
25	**Average (SE)**	**7.0**	**37**	**25**	**12**
26	**Average (RF)**	**1.3**	**9**	**6**	**4**
27	**SD (SE)**	**2.2**	**11**	**5**	**1.8**
28	**SD (RF)**	**0.4**	**3**	**2**	**1.5**

Figure 5.9: Smelting cake-like slag (top position) from Kamafupa 2

Figure 5.10: Refining cake-like slag (left bottom, right top position) from Mkumbi 13A

5.2.5.2 Smelting and refining (tap) flow slags

It has been difficult to systematically differentiate smelting flow slags (Figure 5.11) from refining flow slags (Figure 5.12) in terms of weight and size, because they overlap (Table 5.5). Needless to say, they exhibit flow marks, have greyish colour, and are

relatively less magnetic to bar magnets. Besides the similarity, smelting and refining slag mounds (see Table 5.1) are differentiatable in that the former are absolutely huge heaps including rough and blocky slags (Figure 5.13), while the latter are relatively small including almost flow slags alone (see Figure 5.12).

Figure 5.11: *Malungu* smelting flow slags from Mkumbi area. Note this is a section of the smelting flow slags selected from the *malungu* debris heap (see Figure 5.13) for the purpose of the photograph

Figure 5.12: *Vintengwe* refining (flow) slags from Mkumbi area. Note this heap equals the volume of one refining site material.

Table 5.5: Macroscopic attributes of the smelting and refining (tap) flow slags from Pito, southern Ufipa. Note each of the measurements (mass, length, width, and thickness) represents the average of exact measurements of five (similar) slag samples

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
Smelting tap slags					
1	Mkumbi SE6	60	4	2	1
2	Mkumbi SE6	300	5	4	3
3	Mkumbi SE6	89	6	3	1
4	Chulu SE4	100	8	7	3
5	Chulu SE4	200	10	9	2
6	Chulu SE4	230	9	8	3
7	Nantula SE7	420	9	9	2
8	Nantula SE7	500	10	7	3
9	Nantula SE7	700	12	5	2
10	Nangesu SE5	540	13	8	2
Refining tap slags					
11	Mkumbi RF5A	41	3	2	1
12	Mkumbi RF5A	60	5	3	2
13	Mkumbi RF5A	80	6	5	3
14	Kamafupa RF9	100	8	6	3
15	Kamafupa RF9	400	10	8	4
16	Kamafupa RF9	300	9	8	4
17	Tupa RF1	405	11	8	3
18	Tupa RF1	500	10	8	3
19	Tupa RF1	250	10	6	2
20	Nangesu RF1	355	10	7	3
21	**Average (SE)**	**313.9**	**8.6**	**6.2**	**2.2**
22	**Average (RF)**	**249.1**	**8.2**	**6.1**	**2.8**
23	**SD (SE)**	**217.8**	**2.9**	**2.5**	**0.8**
24	**SD (RF)**	**167.9**	**2.7**	**2.2**	**0.9**

Figure 5.13: M*alungu* smelting slag heap in Ufipa

5.2.5.3 Smelting tuyère-mould slags

Tuyère-mould slags (Figure 5.14) weighed 100-220 g, were 7-15 cm long, and about 2.5 cm in diameter, on average (Table 5.6). The width of the slags is similar to the internal diameter of the respective tuyères (see Table 5.3), because they cooled and solidified inside the tuyères while being tapped. These slags were found exclusively among the smelting slags. This find is in good agreement with the shallow furnace pits of the *malungu*, and the absence of droplet slags, which otherwise would have indicated non slag tapping practise (see Schmidt and Childs 1985: 56). On the other hand, slag tapping with the *vintengwe* furnaces was done through a tunnel, *not* through tuyères (see Greig 1937: 79; Wise 1958: 110), and hence there are no tuyère-mould slags in the refining slag heaps in Ufipa.

Figure 5.14: Smelting tuyère mould slags from Mkumbi, southern Ufipa

Table 5.6: Macroscopic attributes of the smelting tuyère-mould slags from Pito, southern Ufipa. Note each of the measurements represents the average of five measurements of (similar) slag samples.

S/No.	Site	Mass (g)	Length (cm)	Diameter (cm)
1	Mkumbi SE3	75	7	2.4
2	Mkumbi SE3	100	9	2.3
3	Mkumbi SE4	130	11	2.5
4	Mkumbi SE4	105	10	2.4
5	Kamafupa SE17	200	14	2.3
6	Kamafupa SE17	95	14	2.5
7	Nangesu SE12	88	15	2.4
8	Nangesu SE12	120	10	2.4
9	Tupa SE48	220	11	2.3
10	Tupa SE48	130	8	2.3
11	**Average**	**126**	**11**	**2.4**
12	**SD**	**48**	**3**	**0.1**

5.2.5.4 Smithing slag attributes

Morphologically, the smithing slags discovered in particular from Chulu (MLBST10) and Nantula (LPFST14) village sites included hammer scales, droplets, and agglomerated slags. In addition, the smithing sites contained anvils with dolly holes, and hammers. Because the slags from these sites are largely composed of scales and droplets but only a few small agglomerated slags and no smithing hearth cake slags, it is safe to propose that these were secondary smithing sites. Elsewhere in Ubena, where they practised a two stage ironworking process, smelting and smithing, smithing sites comprised of relatively large quantities of agglomerated and smithing hearth cake slags, in addition to hammer scales and droplets (Lyaya 2011). Based on repeated field experience, it is possible to propose whether or not certain smithing slags are the result of primary smithing of the two-stage or secondary smithing of the three-stage process. Lastly, it is also noteworthy that the smithing droplets are often hollow as opposed to the solid smelting droplet slags (see Miller and Killick 2004).

5.3 Presentation and Interpretation of Microscopic Data

5.3.1 Technical Ceramics Chemical Data

5.3.1.1 Set 1: Technical ceramics from Mkumbi smelting 3 and refining 2 sites

On average and based on Table 5.7, the furnace wall (FW) and tuyère (TYR) samples of the two sites are chemically similar indicative of a similar (non-calcareous) clay source or recipe. The test briquettes (TBs) have higher concentration of SiO_2 and Na_2O compared to the furnace wall and tuyère samples. Based on oral evidence the termite mound clay from which the TBs were made was used for the production of technical ceramics, which means that the high concentration of SiO_2 can be related to differences in sampling of the termite mound clays (see Chapter 4 on preparation of TBs). The

higher concentration SiO_2 in the TBs diluted and lowered the concentration per unit volume of the other oxides including alumina, iron, potash, titania, magnesia, lime, and manganese. Although depending on the concentration of the oxides in the TBs, the concentration of sulphide and vanadia was not affected by the problem of sampling silica-rich clay for the TBs (see Table 5.7). It is possible that these oxides have relatively higher concentration in the TBs than in the archaeological samples. The similarities and differences of the three sets of samples in terms of the chemistry and refractory quality are apparent in Figure 5.15. Lastly and on average, it is noteworthy that the increase in silica concentration diluted and lowered the concentration of the trace oxides as well, with the exemption of unaffected zirconia and tungsten oxides (Table 5.8).

Table 5.7: (P) XRF-EDS Major and minor element concentrations of the technical ceramics from Mkumbi smelting 3 and refining 2 sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 5.7; FW=furnace wall, TYR=tuyères, and TB=test briquettes

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
Smelting technical ceramics from Mkumbi site #3													
1	3FW1	0.20	0.92	23.57	64.94	0.03	1.54	0.19	1.00	0.02	0.11	7.47	99.37
2	3FW2	0.19	0.87	22.19	66.59	0.03	1.51	0.20	0.96	0.02	0.13	7.31	99.75
3	3FW3	0.15	0.92	22.67	65.80	0.03	1.55	0.19	1.00	0.02	0.11	7.57	99.85
4	3TB1	0.30	0.53	12.85	78.97	0.02	1.47	0.15	0.72	0.01	0.08	4.91	100.80
5	3TB2	0.27	0.56	16.30	74.26	0.02	1.49	0.19	0.86	0.02	0.08	5.95	100.48
6	3TB3	0.23	0.58	15.39	75.16	0.02	1.45	0.15	0.82	0.01	0.08	6.11	100.86
7	3TYR1	0.17	0.72	24.51	64.50	0.02	1.10	0.23	1.08	0.02	0.12	7.55	99.41
8	3TYR2	0.17	0.81	24.01	65.11	0.02	1.04	0.28	1.03	0.01	0.12	7.40	99.39
9	3TYR3	0.20	0.79	23.45	65.39	0.02	1.10	0.30	1.06	0.01	0.12	7.55	99.56
Refining technical ceramics from Mkumbi site #2													
10	2FW1	0.26	0.67	19.83	70.08	0.02	1.34	0.21	0.92	0.02	0.09	6.55	99.80
11	2FW2	0.18	0.66	20.97	69.10	0.03	1.32	0.21	0.91	0.02	0.10	6.51	99.78
12	2FW3	0.23	0.74	21.68	68.04	0.04	1.47	0.18	0.92	0.02	0.08	6.62	99.49
13	2TB1	0.23	0.69	20.83	69.07	0.03	1.37	0.20	0.92	0.02	0.09	6.56	99.69
14	2TB2	0.29	0.36	10.97	82.04	0.02	1.01	0.10	0.66	0.01	0.06	4.48	101.09
15	2TB3	0.30	0.35	11.26	81.40	0.02	1.07	0.16	0.68	0.01	0.06	4.69	101.09
16	2TYR1	0.18	0.93	24.14	63.77	0.03	1.33	0.48	1.05	0.02	0.13	7.96	99.59
17	2TYR2	0.20	0.99	21.10	68.30	0.01	1.35	0.41	0.96	0.01	0.12	6.54	99.65
18	2TYR3	0.20	0.92	24.25	64.35	0.03	1.31	0.46	1.03	0.02	0.13	7.31	99.22

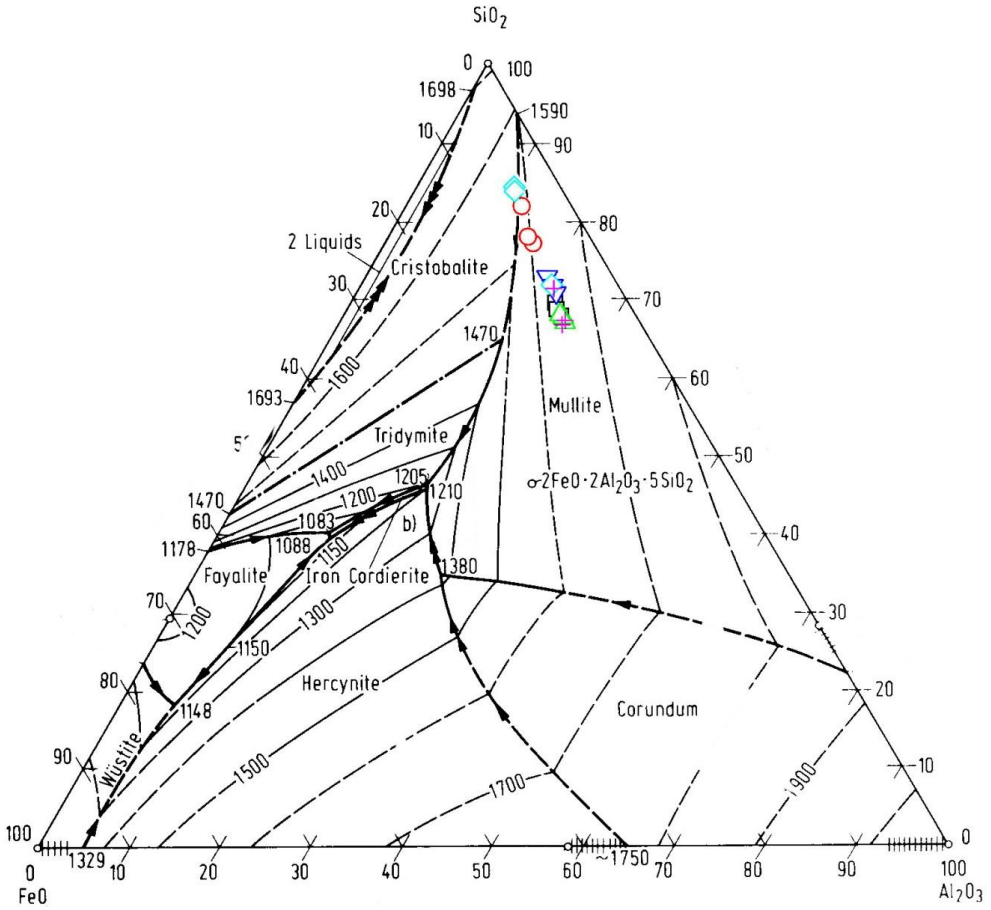

Figure 5.15: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Mkumbi 3 and 2 sites. The squares (black) and downward triangles (blue)=FWs, circles (red) and diamond (sky blue)=TBs, and upward triangles (green) and crosses (pink)=TYRs

Table 5.8: (P) XRF-EDS Trace element concentrations (in ppm) of the technical ceramics from Mkumbi smelting 3 and refining 2 sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 5.8; FW=furnace wall, TYR=tuyère, and TBs=test briquettes

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	Hf	WO_3	PbO	Th
Smelting technical ceramics from Mkumbi 3																		
1	3FW1	55	23	37	47	11	40	25	21	219	15	88	19	44	9	70	33	18
2	3FW2	60	26	51	38	12	41	25	26	234	15	89	20	47	9	71	21	17
3	3FW3	52	28	46	40	11	42	26	22	247	14	87	18	45	9	34	17	19
4	3TB1	56	26	44	42	11	41	25	23	233	15	88	19	45	9	58	24	18
5	3TB2	47	14	19	28	7	28	20	21	229	10	65	20	41	12	139	25	18
6	3TB3	41	13	21	29	7	26	22	22	270	9	68	21	46	11	104	23	19
7	3TYR1	88	31	46	56	14	47	44	31	231	17	110	28	49	8	63	15	18
8	3TYR2	65	31	54	44	12	47	37	27	228	15	96	27	46	8	110	15	18
9	3TYR3	80	32	46	57	14	46	42	30	229	15	110	28	46	8	52	15	18
Refining technical ceramics from Mkumbi 2																		
10	2FW1	80	30	53	48	13	49	33	28	264	14	114	26	50	11	12	16	19
11	2FW2	67	30	40	48	13	45	34	28	255	15	117	26	58	10	27	20	19
12	2FW3	56	33	49	50	13	49	34	28	268	13	120	27	50	10	27	17	20
13	2TB1	52	17	39	34	8	35	27	22	231	9	88	22	45	9	45	39	18
14	2TB2	45	21	46	38	9	38	26	24	265	12	89	25	49	11	28	91	20
15	2TB3	57	22	47	37	9	40	26	23	229	11	90	22	46	10	61	92	17
16	2TYR1	77	29	52	56	13	42	27	30	221	17	98	28	43	9	28	14	17
17	2TYR2	83	30	49	54	13	41	27	29	216	16	92	25	41	10	51	14	17
18	2TYR3	86	30	50	67	14	43	29	28	208	17	97	28	44	7	45	14	18

5.3.1.2 Set 2: Technical ceramics from Mkumbi smelting 4 and refining 5B sites

Table 5.9 indicates that the FW and TYR samples from the two sites are chemically similar, and have similar maximum refractory quality (Figure 5.16). It is essential to note that potash and titania (on the figure) were proportionally adjusted and then added to FeO, in order for alumina, silica, and FeO to add up to or exceed 95 wt% before normalisation (for the details of oxide correction factors, see Appendix 5.9). On average, the TBs are more or less similar to the FWs and TYRs, although some TBs from Mkumbi 5B site had slightly high SiO_2 concentration (see Figure 5.16). The high silica concentration in the TBs, which could be related to sampling problems, unsurprisingly, diluted and lowered the concentration of the other oxides in them including the trace oxides (Table 5.10). As well as the slightly imperfect match in SiO_2 concentration (see also Severin *et al*. 2011; Lyaya *et al*. 2012), the similarity in chemical composition of the ceramics can be used to argue that observed termite mound between the sites was used as the source of clay, and both FWs and TYRs were made from a similar and standardized clay recipe.

Table 5.9: (P) XRF-EDS Major and minor element concentrations of the technical ceramics from Mkumbi smelting 4 and refining 5B sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 5.10; FW=furnace wall, TYR=tuyère, and TBs=test briquettes

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
Smelting technical ceramics from Mkumbi site #4													
1	4FW1	0.15	1.06	26.35	59.29	1.18	1.58	1.23	1.13	0.02	0.16	7.85	100.47
2	4FW2	0.15	0.89	23.77	62.21	1.65	2.20	0.78	1.01	0.02	0.14	7.17	101.34
3	4FW3	0.18	0.98	24.14	60.62	1.79	2.38	1.06	1.08	0.01	0.15	7.62	101.54
4	4TB1	0.18	0.70	20.77	67.34	0.89	1.18	0.51	1.07	0.02	0.12	7.23	101.03
5	4TB2	0.27	0.59	18.95	69.92	0.85	1.14	0.28	1.00	0.02	0.11	6.88	101.00
6	4TB3	0.21	0.65	21.33	66.04	0.83	1.11	0.23	1.11	0.02	0.15	8.32	101.12
7	4TYR1	0.23	0.66	19.05	68.90	0.81	1.08	0.76	1.05	0.02	0.13	7.31	101.31
8	4TYR2	0.22	0.65	19.41	68.46	0.80	1.07	0.61	1.07	0.02	0.15	7.53	101.31
9	4TYR3	0.19	0.67	19.69	68.27	0.80	1.06	0.64	1.07	0.02	0.13	7.45	101.25
Refining technical ceramics from Mkumbi site #5B													
10	5BFW1	0.16	0.93	22.74	64.89	0.76	1.02	1.01	1.02	0.02	0.14	7.29	100.55
11	5BFW2	0.16	0.96	21.91	64.91	0.79	1.05	1.51	1.05	0.01	0.15	7.49	100.89
12	5BFW3	0.21	0.97	23.15	63.79	0.88	1.18	1.38	1.02	0.02	0.15	7.26	100.38
13	5BTB1	0.24	0.69	20.13	68.01	0.79	1.05	0.62	1.03	0.02	0.11	7.30	100.88
14	5BTB2	0.07	0.59	22.34	69.88	0.53	0.71	0.32	0.67	0.00	0.07	4.82	99.57
15	5BTB3	0.20	0.60	17.07	72.38	0.87	1.16	0.26	0.90	0.02	0.13	6.40	101.55
16	5BTYR1	0.15	0.75	22.60	65.83	1.09	1.45	0.17	0.96	0.01	0.08	6.90	100.68
17	5BTYR2	0.14	0.77	22.16	66.49	1.04	1.39	0.15	0.93	0.01	0.09	6.83	100.71
18	5BTYR3	0.16	0.68	20.74	67.92	1.04	1.39	0.12	0.91	0.01	0.10	6.92	101.02

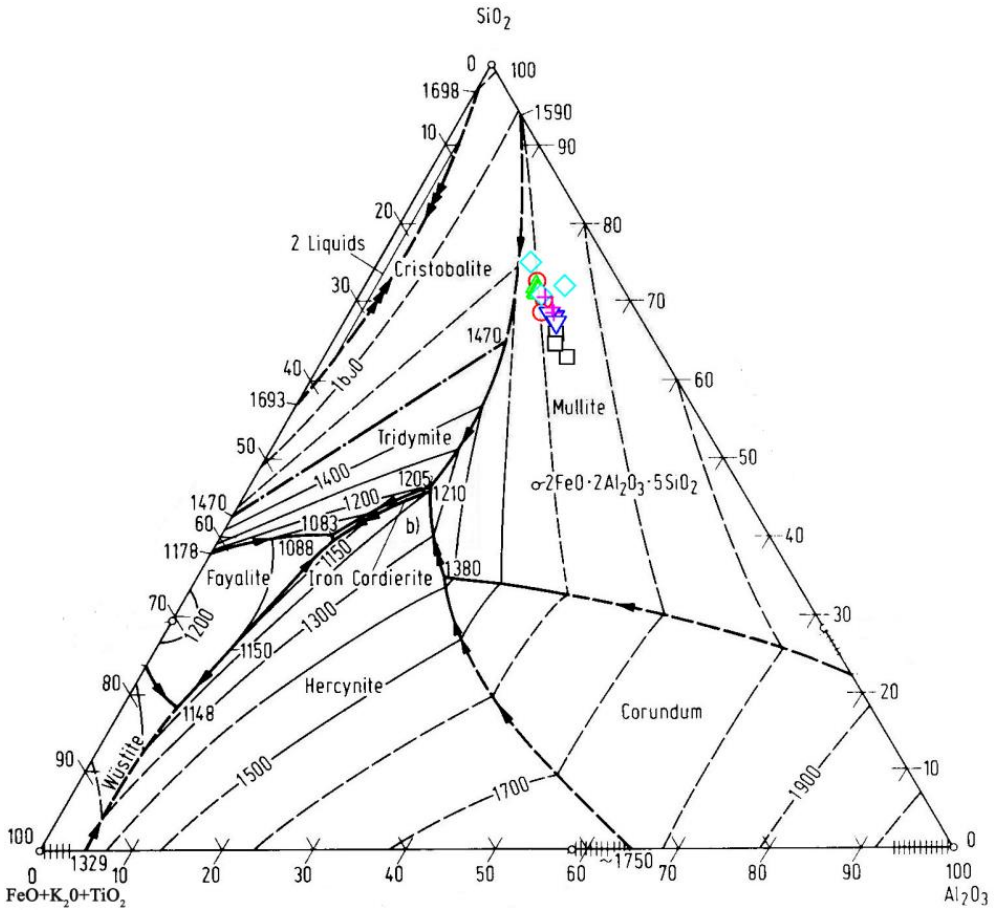

Figure 5.16: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Mkumbi 4 and 5B sites. The squares (black) and downward triangles (blue)=FWs, circles (red) and diamond (sky blue)=TBs, and upward triangles (green) and crosses (pink)=TYRs.

Table 5.10: (P) XRF-EDS Trace element concentrations (in ppm) of the technical ceramics from Mkumbi smelting 4 and refining 5B sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 5.11; FW=furnace wall, TYR=tuyère, and TBs=test briquettes

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	Hf	WO_3	PbO	Th
Smelting technical ceramics from Mkumbi 4																		
1	4FW1	73	41	57	61	15	58	49	33	243	20	137	32	49	9	10	17	17
2	4FW2	65	37	49	56	13	51	48	31	229	16	124	31	49	9	40	16	18
3	4FW3	75	43	63	62	14	51	56	33	243	18	134	31	49	10	68	17	19
4	4TB1	84	29	68	51	14	44	33	31	266	17	103	32	53	11	105	91	20
5	4TB2	87	23	45	47	11	39	25	30	299	15	91	31	51	12	143	144	19
6	4TB3	109	34	70	57	14	47	25	33	242	17	96	33	53	9	145	22	18
7	4TYR1	90	32	46	64	14	45	45	31	210	17	124	30	45	9	114	16	18
8	4TYR2	70	34	52	70	14	45	41	32	217	18	141	31	48	10	98	17	19
9	4TYR3	55	39	47	64	14	46	40	32	216	18	128	30	50	9	79	15	18
Refining technical ceramics from Mkumbi 5B																		
10	5BFW1	68	33	62	55	13	43	49	30	206	16	126	30	46	9	79	19	17
11	5BFW2	80	32	56	58	14	46	56	32	222	18	138	32	49	9	62	25	17
12	5BFW3	90	34	50	57	14	47	61	32	230	17	136	27	44	9	31	15	18
13	5BTB1	87	30	81	51	12	43	34	30	232	17	99	30	49	9	64	27	19
14	5BTB2	35	20	42	32	8	30	25	21	198	13	93	23	35	6	37	33	12
15	5BTB3	76	26	55	51	11	42	26	31	229	14	103	30	49	9	92	22	18
16	5BTYR1	72	25	44	43	13	47	26	21	220	15	89	19	45	8	42	14	17
17	5BTYR2	39	29	45	45	13	44	25	23	219	15	94	20	42	9	61	15	18
18	5BTYR3	55	26	37	43	13	46	26	22	223	15	93	19	45	10	62	18	19

5.3.2 Slag Chemical Data

I aimed at differentiating smelting from refining slags chemically. My prediction was that because only the smelted impure iron pieces and charcoal were charged in the *vintengwe* (e.g. Greig 1937; Wise 1958), reduction or rather complete chemical separation of the impurities (slags) from iron would decrease FeO concentration and increase the concentration of the other slag oxides per unit volume. Unfortunately, this prediction was not supported by the chemical data (see Phase 1 and Phase 2 analyses).

5.3.2.1 Phase 1: Slags from random smelting and refining sites

On average, FeO concentration increased in the refining slags: 39-51 wt%, 51-52 wt%, and 51-55 wt% respectively (Table 5.11) indicative of accidental or unavoidable loss of iron or steel droplets (see mineralogy subsection) in the refining slags. This would be expected in iron metallurgy, because slag (e.g. cake, smithing slags) close or in contact with iron or steel would contain more iron oxides, particles, or droplets (see Miller and Killick 2004; Killick and Gordon 1987: 28). The increase in FeO concentration, and alumina: 10-12 wt% and 7-10 wt% for Kamafupa and Tupa sites, consequently lowered the concentration of silica: 43-33 wt%, 34-32 wt%, and 40-32 wt% respectively. Also the concentration of the other oxides including potash, lime, phosphate, and magnesia were reduced, while titania and manganese concentrations were more or less unaffected (Table 5.11). Considering new data excluding the iron droplets (Appendix 5.12), the refining (and smelting) process was technically efficient (Figure 5.17), because the slags cluster into the Optimum 1 efficient zone (e.g. Rehren *et al*. 2007).

Table 5.11: SEM-EDS major and minor oxide concentrations of the smelting (SE) and refining (RF) slags from Mkumbi, Kamafupa, and Tupa sites. Note the results are the average of three areas measured at *x*50 and are normalised to 100 wt%; full results in Appendix 5.13

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
Set 1: Slags from Mkumbi 6 and 9											
1	6SE1	0.2	12.2	40.5	0.3	1.5	1.1	0.7	1.4	41.9	100
2	6SE2	0.2	12.8	45.9	0.6	2.0	1.5	0.6	0.8	36.4	101
3	9RF1	0.3	11.1	34.1	0.2	1.7	0.7	0.7	1.7	49.3	100
4	9RF2	0.2	11.9	35.1	0.2	1.2	0.8	0.6	1.4	48.4	100
5	9RF3	0.2	9.0	30.3	0.3	1.2	0.7	0.5	1.4	55.8	100
Set 2: Slags from Kamafupa 11 and 9											
6	11SE1	0.4	11.2	26.3	0.5	1.7	1.4	0.4	0.2	58.9	101
7	11SE2	0.8	8.2	41.3	0.6	3.1	1.2	0.3	0.2	44.6	100
8	9RF1	0.2	13.0	33.1	0.3	1.4	0.7	0.6	0.8	50.5	101
9	9RF2	0.2	13.7	36.9	0.4	1.2	0.7	0.5	0.9	46.4	101
10	9RF3	0.4	9.1	27.4	0.4	1.0	1.3	0.4	0.3	59.8	100
Set 3: Slags from Tupa 33, 34, and 8											
11	33SE1	0.1	7.5	39.1	0.2	0.8	0.5	0.6	0.1	51.6	101
12	34SE2	0.2	6.4	40.1	0.2	0.7	0.8	0.3	0.1	51.1	100
13	8RF1	0.2	9.9	37.2	0.3	0.6	1.0	0.6	0.0	51.3	101
14	8CKRF2	0.2	11.0	33.1	0.3	0.9	1.3	0.5	0.5	51.7	100
15	8RF3	0.1	9.3	27.0	0.3	0.7	0.7	0.3	0.7	61.0	100

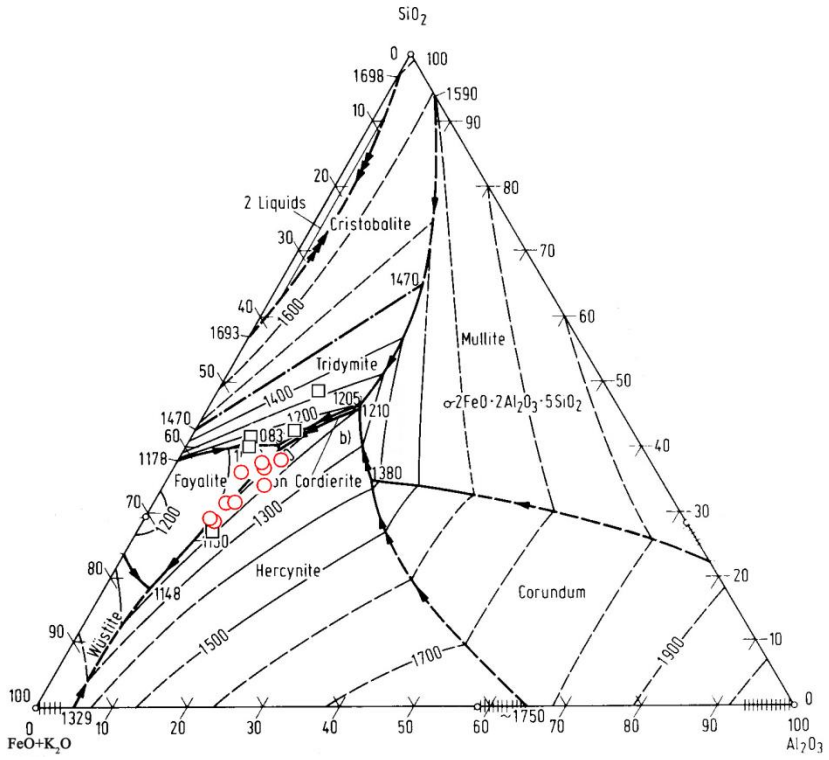

Figure 5.17: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting (black squares) and refining (red circles) slags from Mkumbi, Kamafupa, and Tupa sites

In addition, the concentration of the trace oxides was affected by the increased concentration of FeO and Al_2O_3 (Table 5.12), although this depended on how much of the traces were picked up in the system. On average, the concentration of zinc and barium for the three sites, tungsten for Mkumbi site was decreased; cobalt (Tupa), zirconium and tungsten (Kamafupa) were increased, and the concentration of the remaining of the oxides was more or less unaffected. Because the results were negative to the initial prediction, I tried systematic collection of slags from nearby smelting and refining sites (see Phase 2). The oral evidence assert that the smelted iron pieces were more often refined in the nearby *vintengwe* furnaces, and this means the opposite results presented above could have been the results of sampling slags from unrelated sites and episodes.

Table 5.12: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Mkumbi, Kamafupa, and Tupa sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 5.14

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	Ba	Ce	Hf	Ta_2O_5	WO_3	Th	U
Set 1: Slags from Mkumbi 6 and 9																
1	6SE1	126	8	16	21	74	19	89	14	704	72	10	13	206	8	8
2	6SE2	124	6	27	21	71	19	100	11	619	66	8	9	166	5	8
3	9RF1	130	8	24	5	69	22	84	16	868	70	11	11	142	10	9
4	9RF2	144	8	15	4	62	19	110	19	804	97	10	13	17	10	9
5	9RF3	133	10	25	9	59	21	88	17	733	73	12	13	17	12	11
Set 1: Slags from Kamafupa 11 and 9																
6	11TSE1	174	12	33	28	93	23	59	11	145	68	14	16	19	13	9
7	11FSE2	190	11	31	17	68	25	73	14	134	61	13	17	17	13	10
8	9RF1	161	8	23	7	57	22	90	15	409	64	11	17	15	10	11
9	9RF2	163	8	22	6	51	18	158	29	399	117	11	11	172	9	10
10	9RF3	224	12	40	12	83	18	86	12	222	28	15	18	45	13	13
Set 1: Slags from Tupa 33, 34, and 8																
11	33SE1	130	9	16	12	64	16	107	9	92	17	11	18	18	11	15
12	34SE2	130	10	16	19	51	16	83	16	49	23	13	21	83	11	12
13	8RF1	130	9	21	5	64	15	101	19	73	21	11	17	44	11	9
14	8CKRF2	267	9	15	17	83	18	91	19	280	31	11	11	16	11	10
15	8RF3	186	10	21	4	57	17	87	14	449	35	12	13	57	14	11

5.3.2.2 Phase 2: Slags from systematic (and related) smelting and refining sites

On average and based on Table 5.13, there is a systematic increase in the FeO concentration in the refining slags: 35-51 wt% and 44-50 wt% for the first and second set respectively. One possible explanation is that although the reduction of possible free iron oxides was successful, it was difficult for the smelters or refiners to prevent any accidental addition of the iron droplets (see mineralogy section), or rather 100% chemical separation of the slags from the prills. The increased concentration of FeO consequently diluted and lowered the concentration of silica, that is, 46-33 wt% and 37-36 wt% respectively, and alumina: 13-10 wt% for the second set, while the first set showed no change. Also, on average, the increased concentration of FeO systematically

lowered the concentration of lime by 2-1 wt%, manganese by 2-1 wt%, potash by 2-0.5 wt%, phosphate by 0.5-0.3 wt%, while magnesia, although titania showed no change.

It is noteworthy that semi-bulk area analysis (Appendix 5.15) avoiding the iron droplets and unreacted quartz indicate the refining (and smelting) process was technically efficient, because both the smelters and refiners operated the furnaces at efficient optimum conditions (Figure 5.18; Rehren *et al*. 2007).

Table 5.13: SEM-EDS major and minor oxide concentrations of the smelting (SE) and refining (RF) slags from Mkumbi sites. Note the results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 5.16

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
Set 1: Slags from Mkumbi 3 and 2											
1	3SE3	0.1	11.6	46.3	0.4	1.3	0.8	0.8	1.4	37.2	100
2	3SE4	0.2	12.1	43.6	0.4	1.1	1.4	0.7	0.5	40.0	100
3	3SE5	0.8	11.4	46.0	1.1	1.9	7.4	0.8	3.2	27.4	100
4	3SE6	0.1	11.7	46.8	0.3	1.2	0.6	0.8	1.4	37.1	100
5	3SE7	0.2	11.5	48.0	0.4	1.5	1.1	0.8	1.3	35.1	100
6	2RF4	0.2	10.8	32.6	0.3	0.8	1.1	0.6	0.4	53.3	100
7	2RF5	0.2	10.9	32.4	0.2	1.4	0.7	0.8	1.3	52.1	100
8	2RF6	0.2	12.9	32.3	0.1	1.4	0.5	0.8	1.8	50.0	100
9	2RF7	0.2	12.5	33.8	0.1	1.4	0.9	0.7	1.4	48.9	100
10	2RF8	0.4	12.5	31.9	0.2	1.6	1.6	0.7	1.6	49.5	100
Set 2: Slags from Mkumbi 4 and 5B											
11	4SE8	0.2	14.1	32.5	0.4	0.5	1.3	0.5	1.2	49.3	100
12	4SE9	0.2	13.4	35.5	0.4	0.7	1.9	0.6	1.2	46.1	100
13	4SE10	0.2	13.8	37.6	0.4	0.7	1.8	0.7	1.3	43.6	100
14	4SE11	0.2	12.5	39.3	0.3	1.1	1.8	0.6	2.5	41.7	100
15	4SE12	0.3	12.9	40.2	0.4	1.1	1.8	0.7	2.4	40.2	100
16	5BRF9	0.1	10.2	35.5	0.3	0.7	0.7	0.6	0.3	51.7	100
17	5BRF10	0.1	10.0	37.3	0.4	1.0	0.8	0.6	0.4	49.3	100
18	5BRF11	0.1	9.8	36.7	0.3	0.8	0.6	0.6	0.4	50.5	100
19	5BRF12	0.1	9.9	38.7	0.2	0.7	0.4	0.7	0.5	48.8	100
20	5BRF13	0.1	9.5	36.5	0.4	0.8	0.8	0.5	0.3	51.1	100

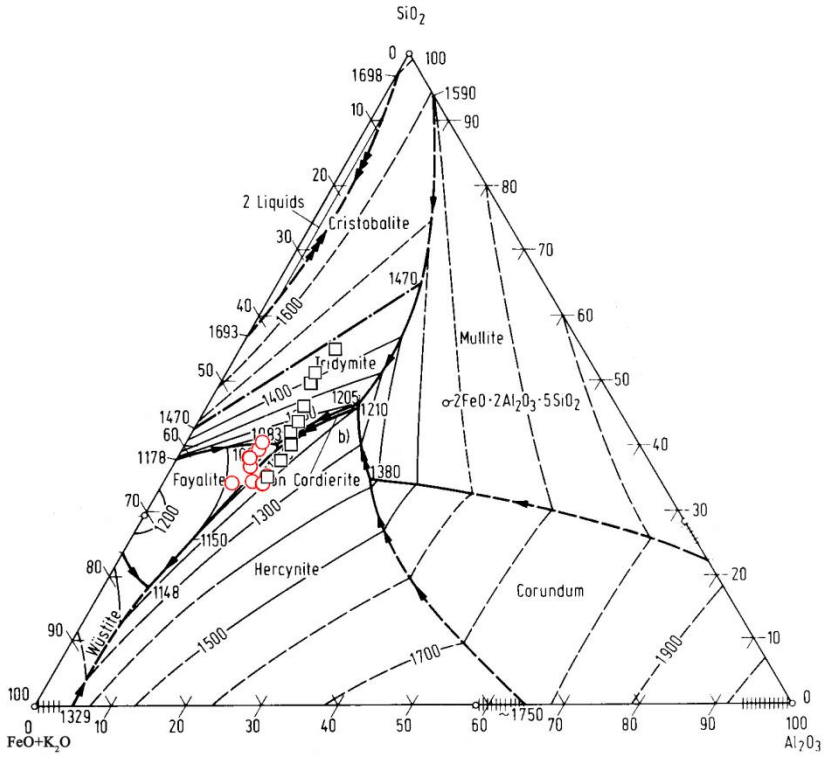

Figure 5.18: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting (black squares) and refining (red circles) slags from Mkumbi sites

Similarly, the concentration of trace oxides was affected by the apparent increase in the FeO concentration (Table 5.14). The concentration of barium, zirconium, cerium, strontium, niobium, and zinc oxides were lowered, cobalt and copper slightly increased, while the concentration of the rest of the oxides including yttrium, hafnium, tantalum, tungsten, thorium, and uranium turned up more or less similar, possibly depending on the nature of the refining process itself.

Table 5.14: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Mkumbi site. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 5.17

S/No.	Sample/ Oxides	Co_3O_4	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	Ba	Ce	Hf	Ta_2O_5	WO_3	Th	U
Set 1: Slags from Mkumbi 3 and 2 sites															
1	3SE3	100	20	29	90	18	176	17	807	114	9	8	21	6	9
2	3SE4	181	17	20	94	16	125	17	389	79	10	13	13	8	8
3	3SE5	86	19	11	431	28	155	31	1694	131	7	10	11	4	9
4	3SE6	99	19	19	80	18	177	15	791	101	9	8	41	6	11
5	3SE7	99	18	20	92	18	171	14	806	106	8	10	11	6	13
6	2RF4	133	36	5	75	19	98	16	116	31	13	13	14	11	12
7	2RF5	130	25	12	73	22	81	14	565	65	12	14	15	11	10
8	2RF6	130	27	14	64	18	86	15	688	58	11	15	14	10	12
9	2RF7	123	24	11	77	19	79	11	556	65	11	14	16	10	10
10	2RF8	123	20	11	123	20	72	17	622	75	11	13	15	10	10
Set 2: Slags from Mkumbi 4 and 5B sites															
11	4SE8	121	20	13	74	22	162	32	638	121	11	15	13	10	12
12	4SE9	168	20	9	107	21	161	30	636	106	11	22	31	9	10
13	4SE10	133	17	11	92	22	174	29	656	115	10	12	14	9	11
14	4SE11	110	26	17	112	20	124	28	1431	111	10	11	12	8	9
15	4SE12	110	21	16	112	19	126	28	1388	106	10	21	13	8	10
16	5BRF9	233	32	11	46	15	95	15	190	44	11	16	14	11	10
17	5BRF10	173	39	5	64	15	95	10	301	57	10	16	11	8	8
18	5BRF11	130	30	8	61	16	104	12	272	53	11	13	27	10	10
19	5BRF12	120	30	9	30	16	117	13	201	47	11	18	14	10	11
20	5BRF13	130	31	9	67	16	109	14	275	53	12	13	16	11	10

5.3.3 Slag Mineralogical Data

While summaries of the microstructures of smelting and refining slags from Mkumbi area (Table 5.15) and Kamafupa and Tupa areas (Table 5.16) are presented separately, for the purpose of comparison, the smelting samples are presented first before the refining samples for each of the areas. In order to compare the technological processes of the three areas, each of the phases is examined and discussed alone, starting with fayalite through others.

Table 5.15: Summary of the phases of smelting (SE) and refining (RF) slags from Mkumbi area

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Wustite	Tap lines	Fe droplets	Fe particles	Leucite	Porosity	Quartz	Others
Smelting slags from Mkumbi 6, 3, and 4												
1	6SE1	√	√	√	-	√	-	-	-	√	√	-
2	6SE2	√	-	√	√	-	-	√	-	√	√	-
3	3SE3	√	-	√	-	√	-	-	-	√	√	√
4	3SE4	√	√	√	-	-	-	√	-	√	-	-
5	3SE5	√	-	√	-	-	-	√	-	√	√	√
6	3SE6	√	√	√	-	-	-	√	-	√	-	-
7	3SE7	√	√	√	-	√	-	√	-	√	√	√
8	4SE8	√	√	√	-	√	-	-	-	√	-	-
9	4SE9	√	√	√	-	√	-	-	-	√	-	√
10	4SE10	√	√	√	-	-	-	-	-	√	-	-
11	4SE11	√	√	√	-	-	-	-	-	√	-	√
12	4SE12	√	√	√	-	-	-	-	-	√	-	√
Refining slags from Mkumbi 9, 2, and 5B												
13	9RF1	√	√	√	-	√	√	-	-	√	√	-
14	9RF2	√	√	√	-	-	√	-	-	√	√	-
15	9RF3	√	√	√	-	√	√	-	-	√	√	-
16	2RF4	√	-	√	-	√	√	-	-	√	-	-
17	2RF5	√	√	√	-	√	√	-	-	√	-	-
18	2RF6	√	√	√	-	-	√	-	-	√	-	-
19	2RF7	√	√	√	-	√	√	-	-	√	-	-
20	2RF8	√	√	√	-	√	√	-	-	√	-	-
21	5BRF9	√	-	√	-	√	√	-	-	√	√	-
22	5BRF10	√	√	√	-	-	√	-	-	√	-	-
23	5BRF11	√	-	√	-	-	√	-	-	√	-	-
24	5BRF12	√	-	√	-	-	√	-	-	√	√	-
25	5BRF13	√	-	√	-	√	√	-	-	√	-	-

Table 5.16: Summary of the phases of smelting (SE) and refining (RF) slags from Kamafupa and Tupa areas

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Wustite	Tap lines	Fe droplets	Fe particles	Leucite	Porosity	Quartz	Others
Smelting and refining slags from Kamafupa 11 and 9												
1	11SE1	√	√	√	√	-	-	-	√	√	√	-
2	11SE2	√	√	√	√	-	-	√	√	√	√	-
3	9RF1	√	√	√	-	√	√	-	-	√	√	-
4	9RF2	√	√	√	-	√	√	-	-	√	√	-
5	9RF3	√	√	√	-	√	√	-	-	√	√	-
Smelting and refining slags from Tupa 33, 34, and 8												
6	33SE1	√	-	√	√	-	-	-	-	√	√	-
7	34SE2	√	-	√	√	√	-	√	-	√	√	-
8	8RF1	√	-	√	-	√	√	-	-	√	√	-
9	8CKRF2	√	√	√	-	-	√	-	-	√	√	-
10	8RF3	√	√	√	√	√	√	-	-	√	√	-

5.3.3.1 Fayalite crystals

All the smelting and refining slags from Mkumbi (Table 5.17), Kamafupa and Tupa (Table 5.18) contain fayalite crystals. Both the smelting (Figure 5.19) and refining (Figure 5.20) crystals are thin, skeletal, and elongated indicative of rapid cooling, apparently outside the furnace (see also tap lines sub-section). Based on the chemical composition (see Table 5.17, Table 5.18) they are pure fayalite crystals which contain 2 molecules of FeO and 1 molecule of SiO_2 ($2FeO.SiO_2$), although sample 3SE5 from Mkumbi contained impure fayalitic mineral, apparently knebelite (Bachmann 1982: 14) for MnO replaces some FeO concentration ($2(FeO.MnO).SiO_2$). In addition to these oxides, the crystals, in order of high concentration, contain MgO, Al_2O_3, P_2O_5, TiO_2, and CaO oxides as well.

Table 5.17: SEM-EDS chemical composition of fayalite in the smelting (SE) and refining (RF) slags from Mkumbi area. Note the results are the average of three spectra and are normalised to 100 wt%; the full results in Appendix 5.18

S/No.	Sample/ Phases	MgO	Al_2O_3	SiO_2	P_2O_5	CaO	TiO_2	MnO	FeO	Total
Smelting slags from Mkumbi 6, 3, and 4										
1	6SE1	1.0	0.9	32.1	0.3	0.2	0.2	2.0	63.0	100
2	6SE2	1.0	0.0	31.0	0.1	0.1	0.0	1.3	66.4	100
3	3SE3	0.6	0.0	30.5	0.1	0.1	0.0	2.1	66.6	100
4	3SE4	1.3	0.0	32.1	0.1	0.1	0.1	1.0	65.3	100
5	3SE5	3.6	0.0	31.1	0.5	0.6	0.0	6.2	57.9	100
6	3SE6	0.7	0.0	30.6	0.0	0.0	0.0	2.2	66.4	100
7	3SE7	0.6	0.0	31.1	0.1	0.0	0.0	2.0	66.1	100
8	4SE8	0.6	0.4	30.7	0.2	0.1	0.1	1.7	66.3	100
9	4SE9	0.7	0.1	31.0	0.2	0.1	0.1	1.7	66.1	100
10	4SE10	0.7	0.5	30.7	0.2	0.1	0.2	2.0	65.8	100
11	4SE11	0.6	0.1	30.4	0.2	0.1	0.1	3.9	64.4	100
12	4SE12	0.7	0.1	31.4	0.1	0.1	0.0	3.9	63.7	100
Refining slags from Mkumbi 9, 2, and 5B										
13	9RF1	0.6	0.6	31.5	0.1	0.2	0.3	2.5	63.9	100
14	9RF2	0.5	0.3	31.2	0.1	0.1	0.2	1.9	65.6	100
15	9RF3	0.4	0.4	30.4	0.1	0.1	0.2	1.9	66.5	100
16	2RF4	0.4	0.4	30.6	0.0	0.1	0.1	0.1	68.3	100
17	2RF5	0.6	0.4	30.6	0.2	0.0	0.2	1.6	66.3	100
18	2RF6	0.7	0.5	30.6	0.1	0.0	0.2	2.2	65.9	100
19	2RF7	0.8	0.7	29.8	0.1	0.1	0.3	1.9	66.3	100
20	2RF8	1.1	0.8	29.8	0.1	0.1	0.3	2.2	65.5	100
21	5BRF9	0.5	0.1	30.3	0.1	0.1	0.0	0.4	68.7	100
22	5BRF10	0.4	0.2	30.6	0.1	0.1	0.1	0.5	68.0	100
23	5BRF11	0.4	0.1	30.6	0.1	0.1	0.0	0.6	68.0	100
24	5BRF12	0.2	0.2	31.1	0.0	0.0	0.3	0.4	67.8	100
25	5BRF13	0.6	0.2	29.9	0.2	0.1	0.1	0.6	68.5	100

Table 5.18: SEM-EDS chemical composition of fayalite in the smelting (SE) and refining (RF) slags from Kamafupa and Tupa areas. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Phases	MgO	Al_2O_3	SiO_2	P_2O_5	CaO	TiO_2	MnO	FeO	Total
Smelting and refining slags from Kamafupa 11 and 9										
1	11SE1	0.6	0.2	31.2	0.1	0.6	0.1	0.4	66.9	100
2	11SE2	0.6	0.2	31.3	0.3	0.2	0.0	0.3	67.2	100
3	9RF1	0.5	0.6	30.9	0.2	0.1	0.2	1.0	66.4	100
4	9RF2	0.6	0.8	31.3	0.2	0.1	0.1	1.2	65.7	100
5	9RF3	1.0	0.5	31.2	0.2	0.3	0.1	0.4	66.3	100
Smelting and refining slags from Tupa 33, 34, and 8										
6	33SE1	0.3	0.2	31.3	0.2	0.1	0.0	0.1	67.9	100
7	34SE2	0.6	0.0	31.2	0.1	0.1	0.0	0.0	67.8	100
8	8RF1	0.3	0.2	30.8	0.2	0.0	0.0	0.2	68.4	100
9	8CKRF2	0.4	0.2	31.1	0.1	0.1	0.1	0.7	67.3	100
10	8RF3	0.4	0.4	31.6	0.3	0.2	0.0	1.0	66.1	100

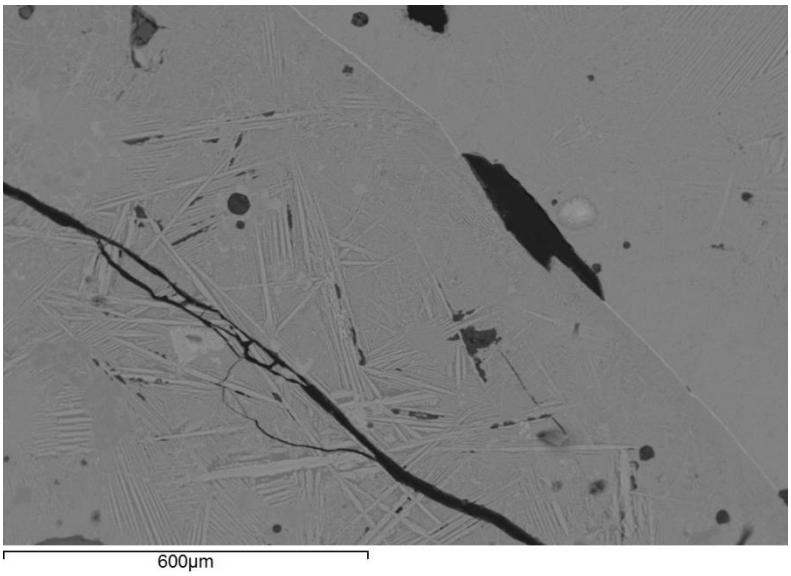

Figure 5.19: The thin and elongated fayalitic microstructures of the smelting slags from Ufipa (4SE8). Note the tap line (white), and zoned hercynite (dark at the cores).

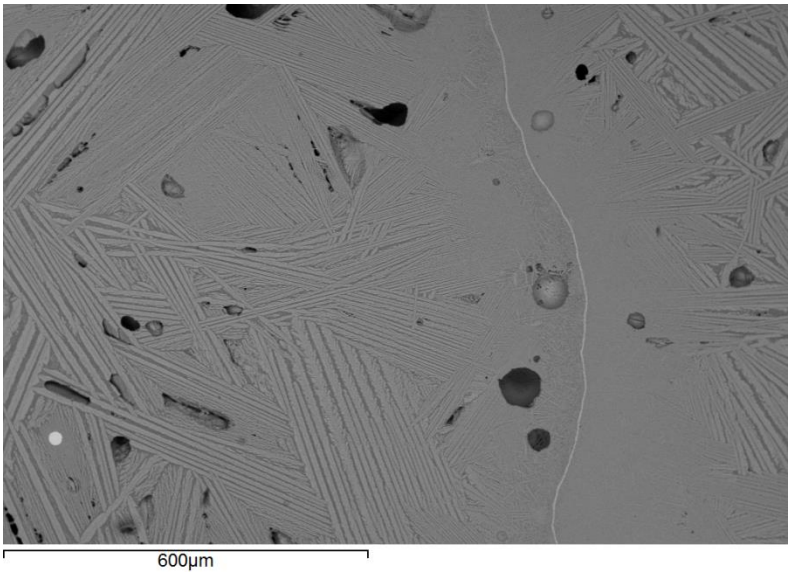

Figure 5.20: The thin and elongated fayalitic microstructures of the refining slags from Ufipa (2RF5). Note the tap line and iron droplet (white).

5.3.3.2 Hercynite crystals

Of all the samples, approximately 80% and 68% of the smelting and refining slag samples also contained hercynite crystals (Table 5.19). This relatively large percent is more likely related to the use of Al-rich lateritic ores (see Lyaya *et al*. 2012). The hercynite crystals of both smelting (Figure 5.21) and refining (Figure 5.22) are small in size, supportive of the rapid cooling proposition. The zoning nature (see Figure 5.21) of some of the smelting slags suggest that there was excess iron in the system to form hercynite while the crystals were being formed, which were not accommodated and ended up surrounding the crystals.

On the basis of $FeO.Al_2O_3$ chemistry (Anthony *et al*. 1997: 561), all are pure hercynite crystals. Others included are titania, vanadia, chromia, manganese, and magnesia.

Table 5.19: SEM-EDS chemical composition of hercynite in the smelting (SE) and refining (RF) slags from Mkumbi, Kamafupa, and Tupa smelting and refining slags. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
Smelting slags from Mkumbi 6, 3, and 4										
1	3SE4	0.0	51.6	0.3	0.8	2.8	2.1	0.1	42.3	100
2	3SE6	0.0	46.1	1.0	1.5	3.2	3.1	0.8	44.3	100
3	3SE7	0.1	32.4	0.5	3.4	3.2	4.5	0.6	55.2	100
4	4SE8	0.3	52.3	0.3	0.6	0.6	0.4	0.6	44.9	100
5	4SE9	0.4	49.4	0.3	0.5	0.6	0.5	0.7	47.5	100
6	4SE10	0.4	52.6	0.3	0.5	1.4	1.1	0.7	43.1	100
7	4SE11	0.2	40.8	0.4	1.0	0.8	0.3	1.2	55.3	100
8	4SE12	0.3	46.0	0.7	0.7	0.7	0.4	1.4	49.7	100
Refining slags from Mkumbi 9, 2, and 5B										
9	9RF1	0.1	42.6	1.2	2.3	1.1	0.1	0.8	51.5	100
10	9RF2	0.1	51.9	1.2	1.2	1.6	0.4	0.7	42.4	100
11	9RF3	0.0	40.7	6.1	2.8	0.4	0.1	0.6	48.7	100
12	2RF5	0.1	45.9	0.6	1.9	3.3	2.4	0.6	45.2	100
13	2RF6	0.3	50.7	0.5	1.2	1.4	1.3	0.9	43.8	100
14	2RF7	0.4	47.1	1.0	1.8	1.7	1.5	0.8	45.7	100
15	2RF8	0.6	50.6	0.3	0.9	1.5	1.5	0.8	43.9	100
16	5BRF10	-0.1	47.9	0.4	1.1	1.3	0.8	0.2	48.3	100
Smelting and refining slags from Kamafupa 11 and 9										
17	11SE1	0.7	49.1	0.2	0.4	0.4	0.5	0.2	48.4	100
18	11SE2	0.0	42.0	0.4	1.4	0.2	0.2	0.2	55.5	100
19	9RF1	0.0	47.0	6.8	1.6	0.2	0.0	0.4	43.2	100
20	9RF2	0.3	52.4	0.9	1.0	1.0	0.9	0.4	43.0	100
21	9RF3	0.5	45.0	0.9	1.2	1.3	1.3	0.2	49.5	100
Refining slags from Tupa 34 and 8										
22	8CKRF2	0.5	51.9	0.3	0.6	0.8	1.1	0.1	44.7	100
23	8RF3	0.3	48.9	0.9	0.8	0.6	0.9	0.3	47.2	100

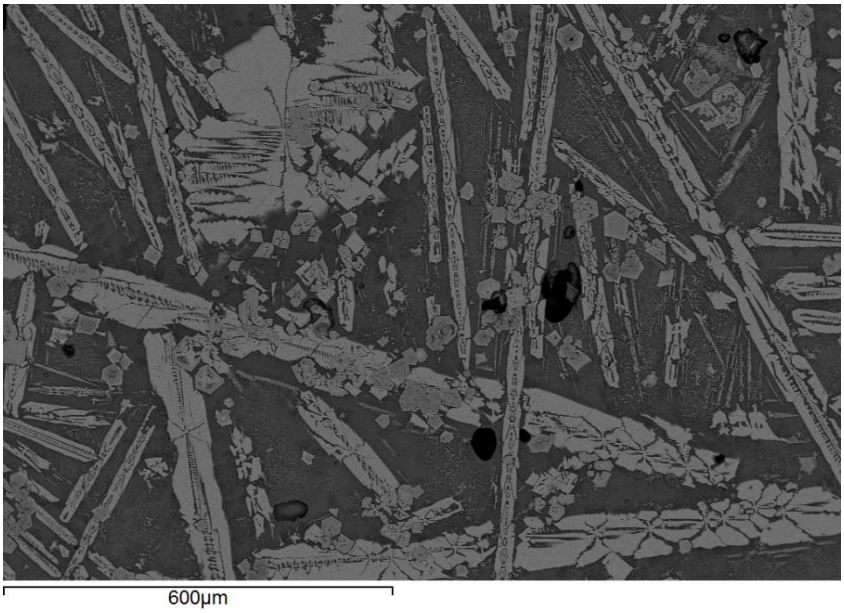

Figure 5.21: Small-in-size and zoned microstructures of hercynite (dark grey) of the smelting slags from Ufipa (4SE11). Note the elongated fayalite (grey) in the glass matrix.

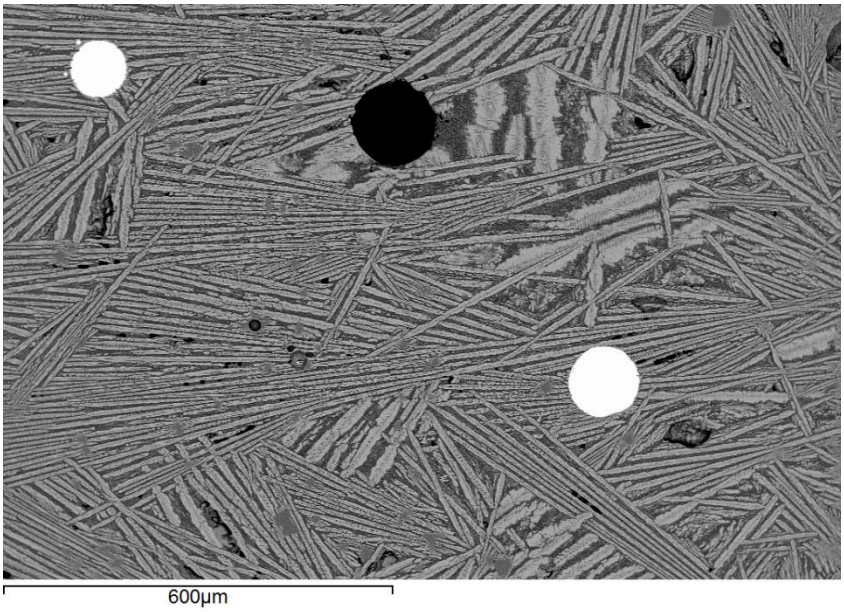

Figure 5.22: Small-in-size microstructures of hercynite (dark grey) of the refining slags from Ufipa (2RF8). Note the iron droplets (white), and fayalite (grey).

5.3.3.3 Glass groundmass

Both smelting and refining slags from Mkumbi (Table 5.20) and Kamafupa and Tupa (Table 5.21) areas have relatively large volume of glass, because they cooled so rapidly that fayalite and hercynite crystals, for instance; had not enough time to grow thicker,

and as a result, much space was left for the groundmass (for example, see Figure 5.21; Figure 5.22). On average, there is more SiO_2 concentration in the smelting slags than in the refining slags for the three sets of samples, apparently because of the respective increase in FeO in the latter. Others included in the glass, in order of descending concentration, are alumina, potash, lime, phosphate, titania, manganese, sulphide, and soda (see Table 5.20, for example).

Table 5.20: SEM-EDS chemical composition of glass matrix in the smelting (SE) and refining (RF) slags from Mkumbi sites. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Phases	Na_2O	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	Total
Smelting slags from Mkumbi 6, 3, and 4												
1	6SE1	0.4	17.0	45.0	0.6	0.0	1.8	1.9	1.2	1.2	30.4	100
2	6SE2	0.2	17.0	56.8	0.8	0.0	3.8	2.4	0.8	0.5	17.0	100
3	3SE3	0.1	16.6	57.1	0.7	0.2	2.2	1.4	1.1	0.7	19.9	100
4	3SE4	0.1	13.6	53.6	0.7	0.2	1.1	4.0	1.2	0.5	25.1	100
5	3SE5	0.1	14.0	51.9	1.3	0.2	2.5	9.9	1.3	2.1	16.4	100
6	3SE6	0.1	17.6	55.8	0.5	0.1	9.4	1.4	1.2	0.6	13.3	100
7	3SE7	0.0	14.3	52.4	0.9	0.1	1.7	2.1	1.2	1.2	25.9	100
8	4SE8	0.1	21.8	43.0	0.4	0.2	1.0	3.3	0.9	0.9	28.4	100
9	4SE9	0.1	22.6	47.2	0.6	0.2	1.1	4.8	1.3	0.9	21.3	100
10	4SE10	0.1	18.3	43.2	0.6	0.2	0.7	3.0	1.0	1.3	31.6	100
11	4SE11	0.1	16.4	48.8	0.5	0.0	1.4	3.2	1.0	2.2	26.3	100
12	4SE12	0.1	13.9	50.8	0.4	0.2	1.0	4.2	0.9	2.2	26.2	100
Refining slags from Mkumbi 9, 2, and 5B												
13	9RF1	0.2	21.6	41.1	0.4	0.4	3.8	1.7	1.6	1.1	28.0	100
14	9RF2	0.1	19.0	40.5	0.3	0.0	1.7	1.5	1.1	1.2	34.0	100
15	9RF3	0.3	14.9	47.6	1.1	0.4	5.2	3.1	1.1	0.8	23.9	100
16	2RF4	0.1	18.5	39.1	0.3	0.0	1.4	2.9	1.3	0.1	36.4	100
17	2RF5	0.3	21.0	44.6	0.7	0.3	4.9	1.8	2.1	0.6	23.9	100
18	2RF6	0.4	15.0	50.4	0.4	0.3	3.4	2.9	1.7	1.2	24.5	100
19	2RF7	0.2	21.2	44.5	0.2	0.1	1.7	4.8	1.5	1.2	24.6	100
20	2RF8	0.2	18.1	45.7	0.3	0.4	2.8	7.4	1.5	1.0	22.8	100
21	5BRF9	0.0	16.4	40.4	0.5	0.0	0.9	1.0	1.0	0.3	39.5	100
22	5BRF10	0.0	14.5	40.1	0.5	0.1	1.5	1.3	1.0	0.4	40.6	100
23	5BRF11	0.0	14.4	42.6	0.4	0.1	1.0	1.2	1.1	0.3	38.9	100
24	5BRF12	0.2	16.1	45.5	0.2	0.2	0.9	0.7	1.0	0.3	34.7	100
25	5BRF13	0.1	17.9	42.6	0.6	0.1	1.5	1.6	1.2	0.4	34.2	100

Table 5.21: SEM-EDS chemical composition of glass matrix in the smelting (SE) and refining (RF) slags from Kamafupa and Tupa sites. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Phases	Na_2O	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	Total
Smelting and refining slags from Kamafupa 11 and 9												
1	11SE1	0.4	21.9	55.3	0.2	0.0	20.0	0.1	0.0	0.0	1.5	100
2	11SE2	0.4	21.8	56.3	0.0	0.1	19.7	0.0	0.0	0.0	1.6	100
3	9RF1	0.2	14.3	49.0	0.6	0.0	3.2	2.5	1.1	0.6	27.6	100
4	9RF2	0.1	20.7	42.5	0.3	0.0	1.8	1.0	0.7	0.7	31.8	100
5	9RF3	0.3	15.6	39.6	2.7	0.4	6.8	10.2	0.5	0.1	22.7	100
Smelting and refining slags from Tupa 33, 34, and 8												
6	33SE1	0.1	13.8	52.7	0.4	0.1	1.5	1.8	0.5	0.1	29.0	100
7	34SE2	0.1	17.5	60.1	1.0	0.2	2.6	3.8	0.3	0.0	14.5	100
8	8RF1	0.2	20.4	44.2	0.4	0.0	1.3	2.4	1.1	0.1	30.1	100
9	8CKRF2	0.1	17.1	50.5	1.0	0.3	3.8	5.8	1.6	0.2	18.9	100
10	8RF3	0.3	15.0	36.9	2.6	1.1	8.8	7.1	0.6	0.2	25.2	100

5.3.3.4 Wüstite crystals

No wüstite crystals were seen in the smelting and refining slags from Mkumbi (Table 5.15), while smelting slags from Kamafupa and Tupa exhibited some wüstite crystals (see Table 5.16, Figure 5.23). Its complete absence or rather the presence of just a few wüstite crystals in the smelting slags suggests that even the smelting process was efficient by itself, although smelting laterites can potentially produce lean slags (see Killick and Gordon 1989). Disregarding negligible little and secondary wüstite only in 8RF3 (furnace) sample from Tupa (Figure 5.24), the absence of wüstite in the refining slags is justifiable, because the metal droplets indicate highly reducing conditions (see next sub-section).

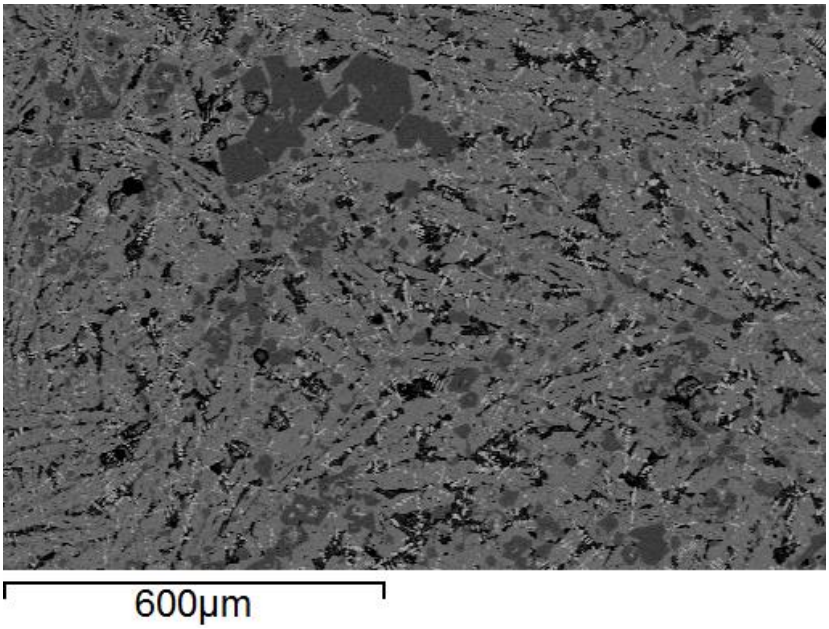

Figure 5.23: SEM-BSE image of some wustite crystals (white) in the smelting slags (11SE1). Note hercynite crystals (dark grey), and (possibly furnace) fayalite (grey).

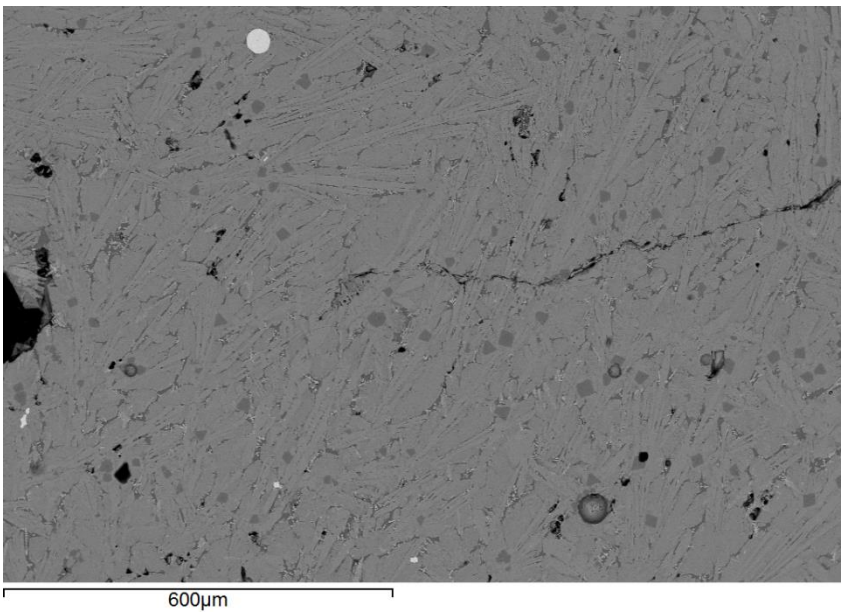

Figure 5.24: SEM-BSE image of little secondary wustite crystals (white in glass matrix) in the refining slag (8RF3). Note round metal droplets (white), hercynite (dark grey), and interconnected fayalite (grey).

5.3.3.5 Tap lines

Some smelting and refining slags from the three areas, depending on where or how they cooled, had typical magnetite tap lines (see Figure 5.19; Figure 5.20 above) indicative

of slag tapping practise for both the first and second stage. While being tapped outside the furnaces, apparently through tuyères, for the smelting process, and through tunnels, for the refining process (see macroscopic data presented earlier), the slag cooled rapidly as attested by the small and thin size of the microstructures of fayalite and hercynite, for example. In addition to the smelting tuyère-mould slags (see macroscopic data), this information is critical, because no one has ever verified the slag tapping hypothesis in Ufipa (for similar view, see Mapunda 2010: 73).

5.3.3.6 Iron droplets

No smelting slags had the perfect round iron droplets, but all the refining slags, whether furnace or tap, exclusively contained *circa* 5-15 droplets per analysed surface (see Figure 5.20; Figure 5.22; Figure 5.24). Their 'liquid' or 'droplet' shape, in addition to the absence of wüstite, is strongly indicative of highly reducing conditions in the *vintengwe* furnaces (see Tholander and Blomgren 1985: 423). To reach such conditions, better skilled smelters or refiners, supposedly ensured an optimum air supply into the furnace, CO/CO_2, and fuel to iron ratios. Unfortunately, the conditions were heterogeneous in the furnace, because carbon content in the droplets is greatly variable, *circa* 0.1-6 wt% (Appendix 5.19). Based on average chemical data of the droplets (Table 5.22) cast iron with pockets of high carbon steel could have been produced, but there is no ethnographic evidence for liquid cast iron in Ufipa. It can alternatively be hypothesized that solid carbon-rich steel with sporadic pockets of cast iron were produced, because the slag matrix is dominated by olivine crystals, and, there is higher concentration of FeO (see Rehren and Ganzelewski 1995; Crossley 1995; see also Chapter 10 on Discussion). Whichever the case, it is reasonable to argue that the smelters essentially may have eventually targeted to produce (low to medium) carbon

steel implements, because they massively decarburized the high carbon product during the smithing stage (see Mapunda 2010: 186).

Table 5.22: EPMA composition of the iron droplets in the refining slags from Ufipa

S/No.	Sample/ Elements	Si	P	Al	Cu	As	Mo	Ni	Co	Mn	Fe	C	Total
Refining slags from Mkumbi													
1	9RF1	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.08	0.01	96.76	3.10	99.51
2	9RF3	0.00	0.01	0.01	0.04	0.00	0.01	0.05	0.23	0.05	96.51	3.09	99.45
3	2RF8	0.01	0.01	0.01	0.03	0.00	0.01	0.02	0.14	0.01	96.34	3.43	99.56
4	5BRF9	0.17	0.01	0.02	0.03	0.02	0.05	0.56	0.35	0.00	94.90	3.88	99.16
5	5BRF11	0.00	0.02	0.00	0.03	0.00	0.01	0.17	0.21	0.00	94.49	5.06	100.33
Refining slags from Kamafupa													
7	9RF1	0.00	0.00	0.00	0.05	0.00	0.00	0.04	0.24	0.02	96.73	2.90	99.56
8	9RF2	0.00	0.00	0.00	0.05	0.00	0.00	0.08	0.41	0.01	94.77	4.66	99.16
6	9RF3	0.10	0.03	0.22	0.13	0.25	0.08	1.99	1.17	0.01	94.58	1.44	101.52

5.3.3.7 Iron particles

Most of the smelting slags contain angular iron particles (Figure 5.25) as opposed to the iron droplets presented above. The particles, in addition to the presence of wüstite (see also Mapunda 2010: 175), are suggestive of lower reducing conditions in the natural draft *malungu* furnaces as opposed to highly reducing conditions in the forced draft *vintengwe* furnaces (for similar argument, see Gordon and Killick 1993: 261). With the relatively lower reducing conditions, it is difficult to think that the *malungu* smelting process in Ufipa produced steel with cast iron pockets, because this would logically mean there was no need of the second *vintengwe* stage. So, it is more probable that the *malungu* furnaces exclusively produced impure soft iron.

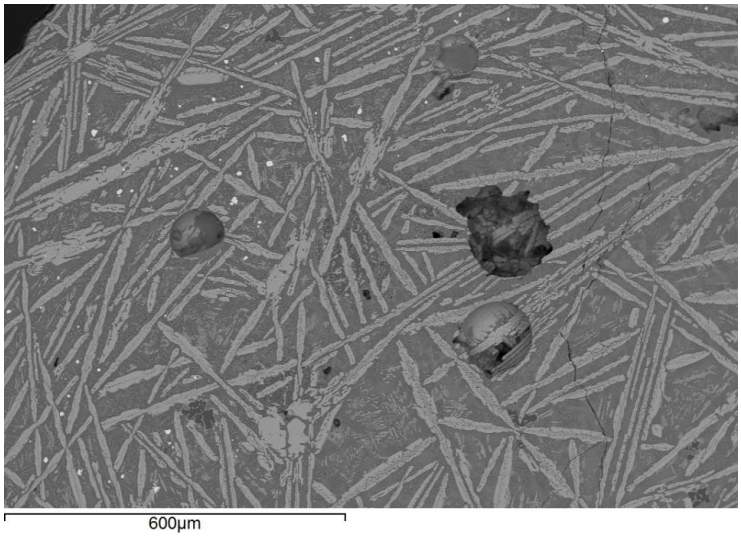

Figure 5.25: SEM-BSE image of angular iron particles (white) in the smelting slag (3SE5). Note the elongated fayalite (grey), and large volume of glass (dark grey)

5.3.3.8 Leucite crystals

Two smelting samples from Kamafupa area alone had leucite crystals (Figure 5.26). On the basis of ($K_2O.Al_2O_3.2SiO_2$) chemistry (Anthony *et al*. 1995b: 462), they were pure leucite crystals, with impurities of iron, titania, magnesia, lime, and soda.

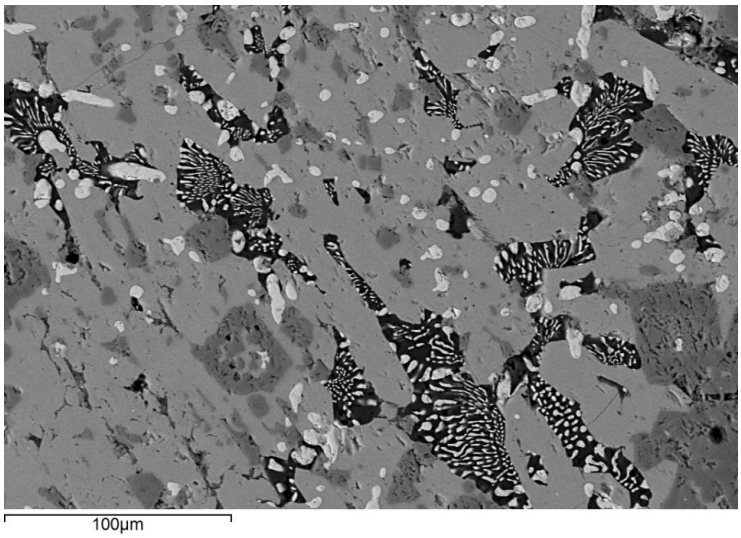

Figure 5.26: SEM-BSE image of leucite particles (black with some wustite) in the smelting slags (11SE2) from Kamafupa. Note the blocky fayalite (grey), wüstite dendrites (white), and large hercynite (dark grey).

5.3.3.9 Porosity and quartz crystals

All the samples were porous. Also, some of the smelting and refining slags incorporated some cracked and uncracked quartz (Figure 5.27). It is unclear whether the cracked quartz particles were part of the original melt or were unavoidably trapped during slag tapping, because the cracks could emanate from sudden and rapid cooling of the melts. Whichever the case, it suffices here to learn that more quartz inclusions in the smelting and refining would consequently lower the concentration of especially FeO. For example, sample 6SE2 from Mkumbi area with high SiO_2 level has unsurprisingly the lowest FeO concentration, and vice versa (see Table 5.11)

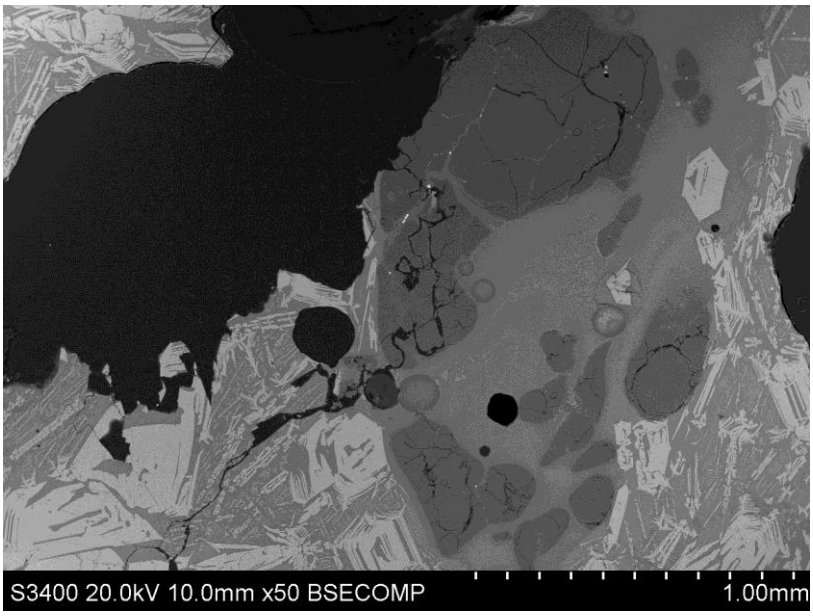

Figure 5.27: SEM-BSE image of reacted quartz particles (grey) in the smelting slags (6SE2) from Mkumbi. Note the fayalite (white grey), glass (light grey), and large pores (black).

5.3.3.10 Other crystals

Because of indistinct mineralogy and chemistry, I have been unable to precisely classify some crystals in 6 samples from Mkumbi area. While mineralogically they look like spinels (Figure 5.28), they are neither 'pure' hercynite nor magnetite, because they have less Al_2O_3 and less FeO to be the former and latter respectively (Table 5.23). I have

named them hercynite-magnetite solid solution, because they are a mixing between pure hercynite and pure magnetite plus some other impurities.

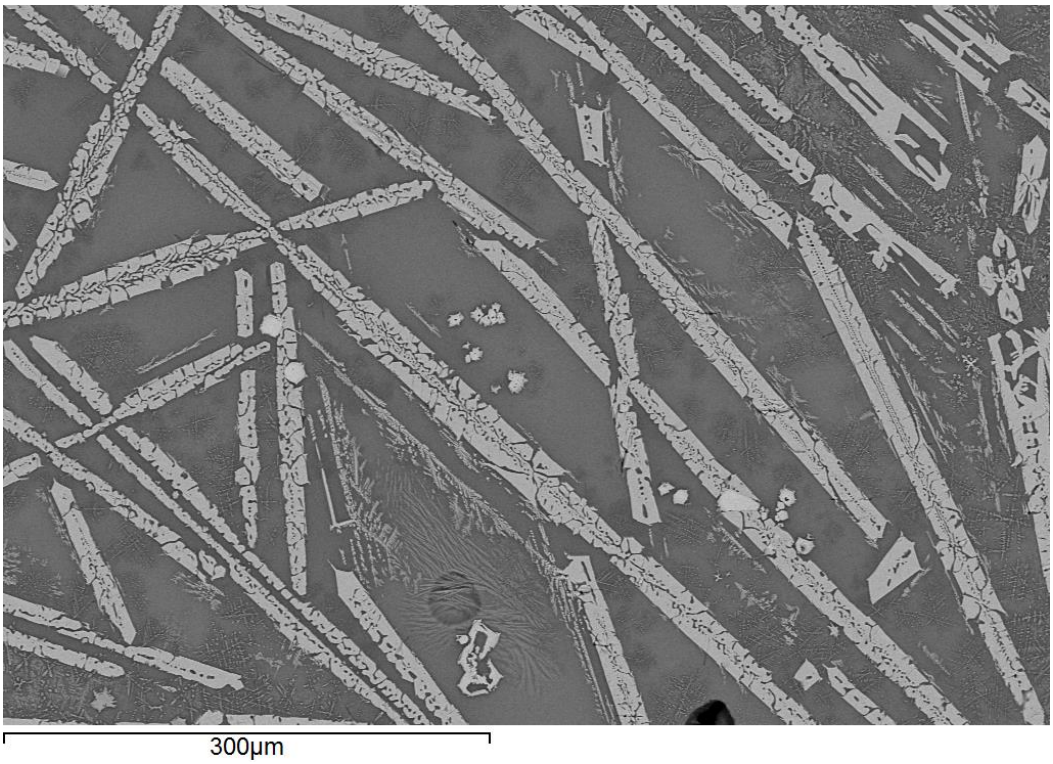

Figure 5.28: SEM-BSE image of the hercynitic spinels (white grey) in the smelting slags from Mkumbi area. Note the fayalite (grey), glass (light grey), and porosity (black).

Table 5.23: SEM-EDS chemical composition of the hercynitic spinels in the smelting slags from Mkumbi area

S/No.	Sample/ Oxides	Al_2O_3	SiO_2	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
1	3SE3	15.0	2.0	5.6	1.8	0.8	0.9	73.4	100
2	3SE5	8.4	0.8	4.6	0.4	0.0	1.6	83.9	100
3	3SE7	10.9	0.7	2.8	1.0	1.4	0.6	82.5	100
4	4SE9	21.4	2.5	3.5	0.2	-0.1	0.5	71.8	100
5	4SE11	24.8	0.7	1.6	0.7	0.3	1.2	70.6	100
6	4SE12	20.6	0.5	1.7	0.7	0.3	1.2	74.8	100

5.4 Discussion of the Aims of the Chapter

The aims of this chapter were presented in Chapter 2 (Previous Archaeological Knowledge in Sumbawanga). They include: (1) verifying the use of termite mounds as chief sources of clay for the construction of *malungu* and *vintengwe* furnaces, and for manufacturing of tuyères as well as examining the refractory quality nature of the technical ceramics, (2) differentiating the *malungu* smelting process from the *vintengwe* refining process, (3) verifying the slag tapping claims in Ufipa, (4) examining the reduction efficiency of the *malungu* and *vintengwe* processes, and (5) discussing the nature of the final products of the *malungu* and *vintengwe* processes. Below is a discussion of these aims based on the new macroscopic and microscopic data presented earlier.

First are the technical ceramics. The chemical data of sets 1 and 2 of ceramics from Mkumbi sites strongly indicate that furnace and tuyères were made from similar clay recipes. Disregarding the relative high concentration of silica in the test briquettes, which possibly resulted from sampling relatively Si-rich high spots of termite mounds with lighter clay components having been washed down slope, the former are chemically similar to the TBs as well. This as well as the similarity in the maximum refractory quality of the three sets of ceramics, 1600-1700 ^{o}C (see Figure 5.15; Figure 5.16) strongly indicative and attest the hypothesis that the termite mounds contiguous to the smelting and refining sites were a chief source of clay for the furnaces and tuyères. While conventionally tuyères would be relatively more refractory than furnaces (see Freestone and Tite 1986; Freestone 1989; Childs 1989a), the similarity in refractory quality with the furnaces is reasonably acceptable, because the clay was refractory enough for the intended functions and purposes, reflective of better skills and repeated experience of the smelters and refiners.

Second is the difference of the remains from *malungu* and *refining* process. (1) As noted earlier, the former is always located on the western side of the mounds (e.g. Greig 1937; Barndon 2004; Mapunda 2010), while the latter is not location-bound, but rather slope-bound practically required for the slag tapping process. (2) The *malungu* furnaces were relatively larger and taller than the *vintengwe* small and short furnaces. The size and height difference is apparently related to the difference in the respective raw materials loaded in the furnaces: bulk (with less FeO-rich, see Mapunda 2010: 99) ores and charcoal for the former and smelted iron pieces and charcoal for the latter. It is uncertain whether the large size was related to demand for high production, but elsewhere in central Africa such tall and large furnaces have been linked with external trade (e.g. van der Merwe and Avery 1987; Gordon and Killick 1993). (3) Needless to say, the *malungu* equipped with about 10 tuyère ports were natural draft, while the *vintengwe* with three tuyère slits were forced draft furnaces. Because of the large size of the former, smelters used multiple tuyères at least three, all arranged horizontally, one on top of the other, and single tuyères per slit was preferred for the latter. While flared tuyère ends are conventionally associated with forced draft furnaces (Childs 1996; Mapunda 2010), exceptionally, the *vintengwe* refining tuyères were not made flared. This information arguably alerts archaeologists to be vigilant for exceptions and extraordinary variation of ironworking (for similar view, see Schmidt 2001). (4) The smelting slags are generally blocky with relatively heavier and larger cake-like slags than the refining slags, although the flow or rather tap slags from both are similar in size, texture, colour, and weight (see Table 5.5). Tuyère-mould slags are exclusively smelting, because slag was tapped through the tuyères, while refiners dug tunnels below tuyères level (see Figure 5.8) for draining the liquid slag outside the *vintengwe*.

Third is verifying the *malungu* and *vintengwe* slag tapping technology. The thin, elongated, and skeletal microstructures of the fayalite and hercynite crystals (e.g. Figure

5.21; Figure 5.28), in addition to the presence of magnetite skins or tap lines (see Figure 5.19; Figure 5.20) in both smelting and refining slags, no doubt attests that slag tapping was practised in Ufipa as argued by the early researchers in the region. This information clears doubts raised by Mapunda (2010: 73) on the need to verify the long-claimed *malungu* slag tapping practise in Ufipa.

Fourth is examining the reduction efficiency of the *malungu* and *vintengwe* processes. The absence of high free iron oxides in the slags conventionally suggests that both the processes were technically efficient (see Figure 5.17; Figure 5.18), although some smelting slags showed up little wüstite (see Figure 5.23; Figure 5.26). The presence of little wüstite crystals in the latter is explainable, because they were eventually reduced and coalesced to iron during the subsequent refining stage. To reach the optimum efficient zone 1 (see Figure 5.17, Figure 5.18; Rehren *et al*. 2007) would have required the smelters and refiners to increase the fuel:ore and fuel:iron ratio respectively. In addition, it is possible that bellowing the *vintengwe* furnaces was more effective and standardized than the natural draft operations (for similar view, see Gordon and Killick 1993). Unfortunately, the latter including the role of labour, experience of the smelters, and medicines cannot be observed normally, but yet it does not mean they were unimportant or absent for the efficiency of the smelting or refining process (see Rehren *et al*. 2007).

Fifth and last is suggesting the nature of the smelted and refined products. Smelters and refiners may have desired two different products from the two processes, but to reach this end, it is no doubt this depended on the efficacy of the reducing conditions. The presence of the wüstite and angular iron particles in the smelting slags on one hand, and the absence of wüstite and presence of iron droplets in the refining slags on the other, strongly suggests that the reducing conditions were apparently lower in the former and higher in the latter. It is possible that the former was meant to produce bloom, while the

latter geared to produce high carbon steel and/or cast iron, because irregular iron particles and wüstite have been associated with 'bloomery' iron production process, and the iron droplets are, among other factors, a key characteristic of a blast furnace (e.g. Tholander and Blomgren 1985: 422; Tholander 1989: 38). Based on the chemical data of the iron droplets (see Appendix 5.19; Table 5.22), it was heterogeneous high carbon steel with cast iron that were systematically produced in Ufipa rather than the liquid cast iron conventionally linked with blast furnaces (e.g. Tholander 1987). The production of heterogeneous solid product, carbon-rich steel with some cast iron pockets, relates to sporadic earlier studies elsewhere on the continent (e.g. Childs 1996; David *et al*. 1989), but does not support Barndon's (2004: 89) suggestion that soft iron was the final product of the *vintengwe* process in Ufipa. In fact, the Fipa clearly knew the difference of the products: the first soft iron was called *untale* or *mtale,* and the second carbon-rich steel with cast iron was called *ululu* or *mlulu* (e.g. Wise 1958: 110; Barndon 2004: 89).

5.5 Summary

Ironworking in Ufipa was a three-stage process. The three stages including smelting, refining, and smithing were different both technologically and functionally. The First *malungu* process more probably produced soft impure iron pieces, the second *vintengwe* process refined and carburised the impure iron to high carbon steel with cast iron as a heterogeneous solid product, and the third *impembo* process was for the forging of implements. The high carbon steel was possibly decarburised to low or medium carbon steel during the third stage (see Mapunda 2010). Both the first and second stages involved slag tapping, and were technically efficient processes. The following chapter addresses whether or not the neighbouring Nyiha people of Mbozi followed the three-stage process as well.

6. Iron and High Carbon Steel Production in Mbozi

6.1 Preamble

This chapter focuses on differentiating the iron refining process from smelting and smithing processes in Mbozi district (Figure 6.1). The land is referred to as Unyiha due to the fact that the majority of the indigenous population are the Nyiha (LOT 2009: 64), a Bantu speaking tribe (Sutton 1969, 1971). Firstly, I present and interpret new macroscopic and microscopic data. Secondly, I provide a discussion of the data in relation to the aims of the chapter. In the end, I provide a summary emphasizing that iron and steel production in Unyiha involved the *vintengwe* iron refining process, an intermediate process between smelting and smithing (primary and secondary) processes.

Figure 6.1: Map of Mbeya region showing the location of Mbozi research area district

6.2 Presentation and Interpretation of Macroscopic Data

6.2.1 Sites: Location, Size, Preservation, and Context of the Material

6.2.1.1 Location

Fieldwork research in Itaka ward was conducted in Malolo, Shihando, Itaka, Hangomba, and Insane villages, and in Kapele ward, Kapoka and Iyendwe villages were studied (Figure 6.2). The archaeological surveys in these villages led to the discovery of 40 ironworking sites, including 20 ore smelting sites, 19 iron refining sites, and one smithing site (see Appendix 6.1 through 6.6). Geographically, the sites are confined between latitudes S (8^o 51' and 9^o 6') and longitudes E (32^o 12' and 32^o 48'), and on altitude ranging from 1385-1595 m above mean sea level. Ore smelting and bloom refining sites were located within 300 m close to water sources such as rivers, ponds, and wells. This distance is in agreement with the distance of within 400 m recorded in Ufipa (Mapunda 2010: 156), and can be used to highlight the importance of water for locating ore smelting and bloom refining sites. Elsewhere in Ufipa, Mapunda (2010: 223) argues that water source was second, after proximity to clay source, among the factors that mattered for the location of sites when they are arranged in order of frequency. All smelting sites in Mbozi are located near termite mounds, even though most of the mounds have collapsed owing to high demand and use for arable lands there are still some signs of them all over.

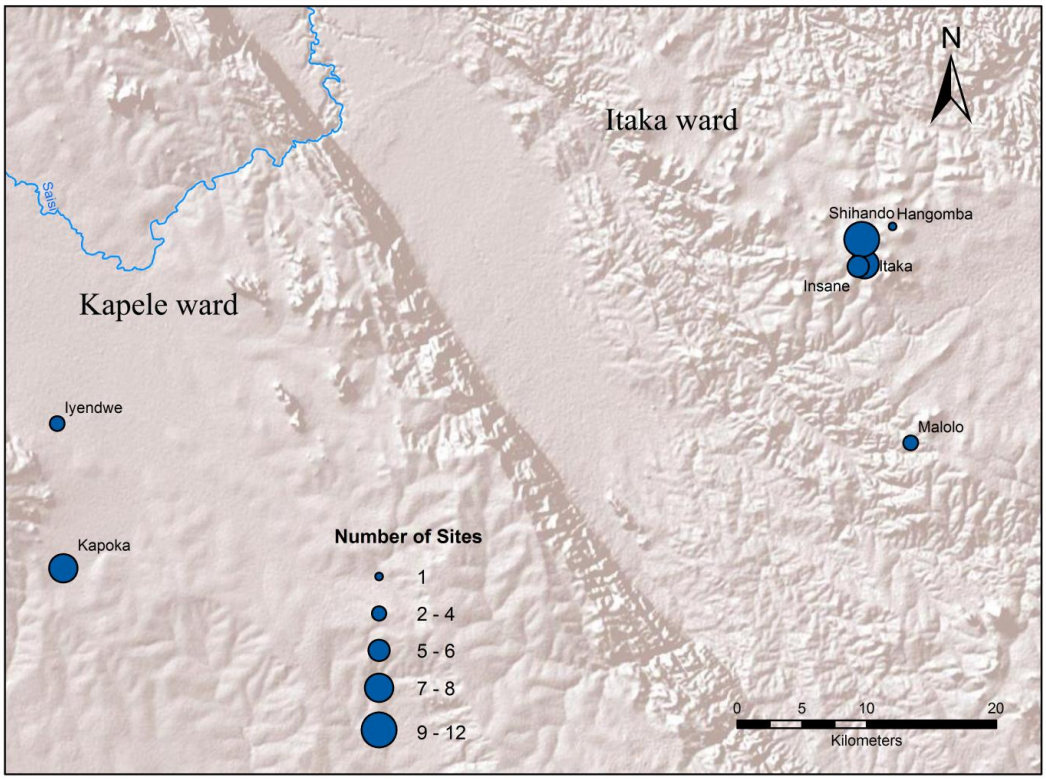

Figure 6.2: Map of Itaka and Kapele wards showing the distribution of the studied villages and number of sites per village

6.2.1.2 Area size

The area of the smelting sites is 32-1146 m^2, while that for the refining sites is 20-380 m^2. This indicates that smelting sites are generally larger than the refining sites. The difference is the function of differences in the size and weight of the bulk raw materials for the two processes. For the same reason, it is no wonder that the area of the smithing site in this area was smaller than both the ore smelting and bloom refining sites (see Appendix 6.1).

6.2.1.3 Preservation

Today, most of the smelting and refining sites are located in people's farms. Some farmers have encircled the ore smelting and bloom refining sites, leaving them uncultivated or rather undisturbed, while some of the sites have evidently been disturbed by farming activities. The smelting and refining sites in Malolo village are in

bushes and are undisturbed by farming activities. According to Gibson Mponzi Nkota (aged 68, interviewed 14th September 2011), and Thomas Mwampumba Nkota (aged 84, interviewed 17th August 2010), both grandsons of a famous iron smelter, called Nkota, the use of smelting and refining areas for farming activities is a recent phenomenon owing to increasing population and high demand for more arable lands.

6.2.1.4 Context of the material

The material and samples described in this chapter were surface collections from the smelting, refining, and smithing sites. The samples included furnace walls, tuyères, potsherds, and slags.

6.2.2 Furnace Attributes

6.2.2.1 *Malungu* smelting furnaces

There were 7 smelting sites with still standing smelting furnaces in Kapele ward. This area that borders Zambia is the most inaccessible area in terms of road transport. Its inaccessibility is perhaps one of many reasons justifying why iron smelting there persisted until the 1950s. The British colonial administrators did not reach this area easily to reinforce the ban on iron smelting activities for imperialistic motives (see Mapunda 2002a, 2003a). In order to get a representative picture of the nature of the smelting furnaces, attributes of the complete smelting furnaces alone have been measured (Table 6.1).

Table 6.1: Smelting (SE) furnace attributes from Kapele ward. Note I = internal, E = external, B = base, M = middle, Top = top, D = diameter, WT = wall thickness, and SD=standard deviation

S/No.	Site/ Attributes	Internal Diameters (m)			External Diameters (m)			Wall thickness			Height	Ports
		IBD	IMD	ITD	EBD	EMD	ETD	BWT	MWT	TWT		
1	Kapele SE1	1.7	1.3	0.85	1.95	1.45	1	0.13	0.08	0.08	3	10
2	Kapele SE2	1.5	1.31	0.9	1.73	1.46	0.99	0.12	0.08	0.05	2.73	10
3	Kapele SE3	1.68	1.32	0.87	1.88	1.47	1	0.10	0.08	0.07	2.7	10
4	Kapele SE4	1.67	1.3	0.86	1.88	1.43	0.98	0.11	0.06	0.06	3	10
5	Kapele SE6	1.6	1.32	0.88	1.8	1.5	1	0.10	0.09	0.06	3	9
6	Kapele SE8	1.6	1.3	0.91	1.85	1.46	1	0.13	0.08	0.05	3	10
7	Iyendwe SE2	1.4	1.31	0.89	1.63	1.47	1	0.12	0.08	0.06	3	10
8	Average	**1.59**	**1.31**	**0.88**	**1.82**	**1.46**	**1.**	**0.11**	**0.08**	**0.06**	**2.92**	**9.86**
9	SD	**0.11**	**0.01**	**0.02**	**0.11**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.14**	**0.38**

The smelting furnaces are large and wide superstructures with a truncated cone chimney, they are very wide at the base, less wide at the middle, and even less wide at the top. Similarly, the external diameters and wall thickness of the furnaces decrease towards the top of the structure. These dimensions give them a truncated cone shape (Figure 6.3). The diameter measurements and height of the furnaces, of between 270 and 300 cm, are more or less similar to those recorded by Brock and Brock's (1965: 97-98). When compared to the *malungu* furnaces of Ufipa (Mapunda 2010: 150), the current smelting furnaces appear similar to the internal diameters of the *malungu* furnaces in Ufipa of about 130-150 cm at the base and 50-95 at the top respectively. When compared to other furnaces recorded elsewhere in Ufipa by Wembah-Rashid (1969: 67) as well as Greig (1937: 78), the smelting furnaces in Mbozi are no exception. The subtle differences observed could easily be the function of acceptable local and spatial variation.

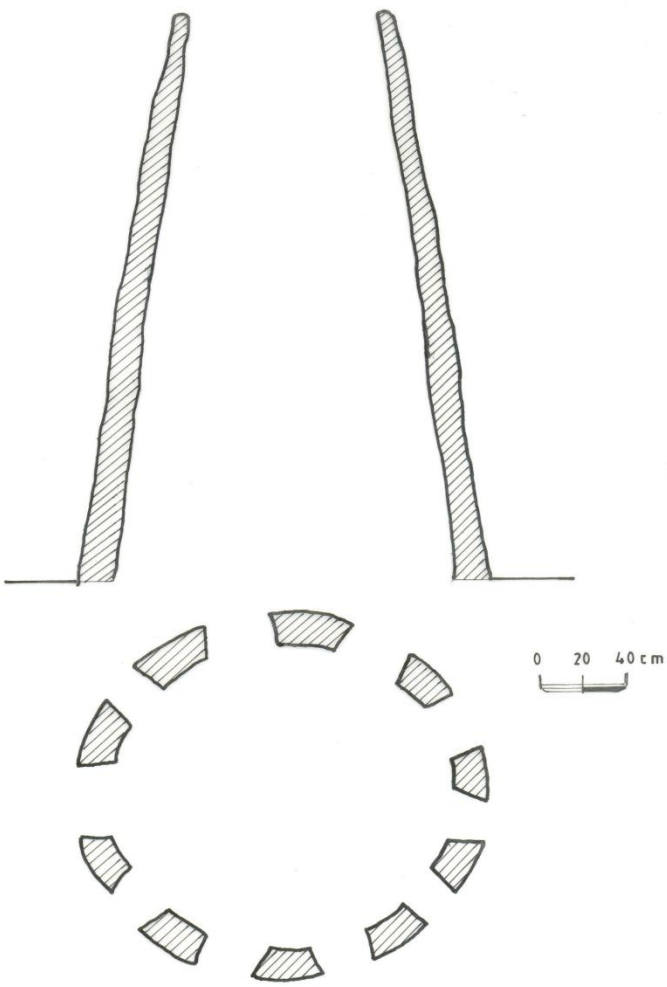

Figure 6.3: Sketch of ore smelting furnaces from Kapele ward

On the walls of the furnaces there are superimposed, 6 to 10 rings, perhaps corresponding to the number of the courses of construction for each of the furnaces (see also Mapunda 2010). Behind the furnace and opposite the mother door between 100 and 150 cm high above ground, there is a peep hole measuring 4 cm as an average diameter. As from its name, the peep hole was used by the chief smelter to peep into the furnace so as to monitor the progress of the smelting process.

Below the tuyères level, the smelting furnaces in Unyiha have shallow depressions, averaging between 10 and 30 cm deep. It is understood from Brock and Brock's (1965: 98) work that slag was tapped through the tuyères. The frequency of tuyère-mould slags

(see slags section) at all smelting sites strongly supports Brock and Brock's (1965) hypothesis.

6.2.2.2 *Vintengwe* refining furnaces

No still standing *vintengwe* furnaces were discovered during my research. According to my informants, this could probably be explained by the fact that they were meant to serve one iron refining episode only. Nevertheless, Brock and Brock (1965: 98) measured and recorded several *vintengwe* furnaces in Itaka, measuring up to 50 cm high and wide, and ones with uniform wall thickness and diameter, similar from the base to the top (for extra details, see Chapter 2 on Previous Archaeological Knowledge in Mbozi). Both the smelting and refining furnaces were constructed from wet clay prepared from nearby the termite mounds.

6.2.3 Tuyères Ports and Tuyères

6.2.3.1 *Malungu* tuyère ports and tuyères per port

On average, the smelting furnaces have 10 tuyère-ports, including 9 ordinary tuyère-ports and 1 mother door (see Figure 6.3), which is consistent with Brock and Brock (1965: 97) who recorded 8-10 tuyère-ports per *ilungu*. The size of the ordinary tuyère ports measured 15-20 cm wide, 25-30 cm high, while the mother door measured 35-40 wide, and 30-35 cm high. It appears that the height of the ports was meant to accommodate 3-4 tuyères that were horizontally arranged, one on top of another. The width was shorter to accommodate *circa* 4 tuyères horizontally arranged, one besides another (for horizontal arrangement of tuyères, one besides another, see next chapter). The mother door was wider and used for 'bloom' collection, and more importantly, because it housed double the number of the ordinary ports, 6-8 tuyères (Kunzitwe Mwashilingi, aged 98, interviewed on the 13th August 2010, and Pattison Helahela aged

71, interviewed on the 12th September 2011; for similar observation elsewhere, see Chaplin 1961: 54; Mapunda 1995a: 50). The fact that most of the smelting sites consisted of multiple tuyères as double, triple, or quadruple tuyères cemented together with slag strengthens the proposition that each of the tuyère ports housed multiple tuyères (Figure 6.4).

Figure 6.4: Triplets tuyères from Shihando smelting sites

6.2.3.2 Tuyère attributes

In terms of physical attributes, the smelting tuyères have external diameter (ED) of 4-7 cm, internal diameter (ID) of 2.5-3.5 cm, and wall thickness of 0.9-1.9 cm (for details, see Table 6.2). The smelters were consistent on the internal diameters indicative of use of a special stick with uniform thickness to make the tuyères (Jonas Elia Mwanakulya, aged 77, interviewed on the 9th September 2011). While making the tuyères, stiff clay was wrapped around the stick soaked in ash to prevent clay from sticking onto it (see also Klapwijk 1986a: 17). Also, the consistency of the internal diameters across sites suggests a high level of uniformity and standardization of the practise. It is the internal diameter (Klapwijk 1986a) and effective rate of bellowing (Avery and Schmidt 1979; Friede and Steel 1986a) that matter as far as efficient air supply into the furnaces is concerned.

Table 6.2: *Malungu* tuyères attributes from Mbozi. Note ED = external diameter, ID = internal diameter, SE=smelting site, and SD=standard deviation

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Shape
1	Itaka SE1	5.1	2.9	1.1	Unflared end
2	Itaka SE6	4.2	3.0	0.6	Unflared end
3	Kapoka SE8	6.3	3.5	1.4	Unflared end
4	Malolo SE1	6.0	3.4	1.3	Unflared end
5	Shihando SE1	5.7	3.1	1.3	Unflared end
6	Shihando SE2	7.0	3.3	1.9	Unflared end
7	Shihando SE3	4.5	2.4	1.1	Unflared end
8	Shihando SE4	5.2	3.0	1.1	Unflared end
9	Shihando SE9	6.2	3.1	1.6	Unflared end
10	Shihando SE11	6.3	3.2	1.6	Unflared end
11	**Average**	**5.7**	**3.1**	**1.3**	
12	**SD**	**0.9**	**0.3**	**0.3**	

No tuyères with flared proximal ends were observed and this can be taken to be indicative of practise of a natural draft technology (Mapunda 2010: 153). Elsewhere in central and eastern Africa, similar tall and large furnaces were operated by natural draft (see Wise 1958: 107; Chaplin 1961: 54; Wembah-Rashid 1969: 66; van der Merwe and Avery 1987; Davison and Mosley 1988: 74). Although tuyères inserted in the ordinary ports were principally used for natural air supply into the furnace throughout the smelting process, Mapunda (2010: 154) writes that those in the *palinyina* were used for air supply into the furnace and slag tapping.

6.2.3.3 *Vintengwe* tuyère ports and tuyères per port

These were small with three tuyère ports, each of which housed one tuyère (see also Brock and Brock 1965). In addition to the slits, *vintengwe* differed markedly in that they had one big tunnel dug down the slope for draining slag outside the furnace.

6.2.3.4 Tuyère attributes

No complete tuyères were recovered except for fragmented ones, the broken pieces usually measured between 3 and 15 cm long, and consisted of distal parts often coated with slag, the middle or body, and proximal segments. The details of the physical attributes of the tuyères are presented in Table 6.3.

On average, the refining tuyères are very similar to the smelting tuyères in terms of external diameters (ED), internal diameter (ID), and wall thickness indicative of use of the similar methods and practise, although the refining tuyères should have been relatively shorter, owing to the small size of the *vintengwe* (see previous chapter).

Table 6.3: *Vintengwe* tuyères attributes from Itaka ward. Note ED = external diameter, ID = internal diameter, RF=refining site, and SD=standard deviation

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Shape
1	Itaka RF2	6.3	3.1	1.6	Unflared end
2	Itaka RF4	5.4	3.3	1.1	Unflared end
3	Insane RF1	7.0	3.5	1.8	Unflared end
4	Insane RF4	6.3	3.3	1.5	Unflared end
5	Insane RF5	5.2	3.0	1.1	Unflared end
6	Insane RF6	4.9	3.1	0.9	Unflared end
7	Shihando RF5	5.0	3.2	0.9	Unflared end
8	Shihando RF6	6.6	3.4	1.6	Unflared end
9	**Average**	**5.8**	**3.2**	**1.3**	
10	**SD**	**0.8**	**0.2**	**0.3**	

As with the *malungu*, no flared tuyères were recovered at *vintengwe* sites. The proximal tuyère ends were unflared. While lack of flared tuyères suggests a natural draft operation (Childs 1996; Mapunda 2010), it is noteworthy that the oral evidence maintains that the *vintengwe* were operated by forced draft mechanism. Therefore, the association of unflared tuyères with natural draft technology alone is insufficient. Based on the small size and number of tuyères of the *vintengwe*, it is not surprising that they were operated by forced draft mechanism (see van der Merwe and Avery 1987: 149).

6.2.4 Slag Attributes

For the sake of comparison, smelting and refining slags are generally classified into furnace (cake-like) slags, flow or tapped slags, and tuyère-mould slags, depending on place of solidification. The morphology of smithing slags are separately presented in the end of this section.

6.2.4.1 Smelting and refining cake-like slags

On average, the smelting cake slags (see Table 6.4) are heavier and larger in size than the refining cake slags (Table 6.5). The difference in weight and size is perhaps the function of the differences in the sizes of the respective furnaces and the bulk of the materials charged into the respective furnaces (see furnace sections above). Besides the differences, smelting and refining cake-like slags are morphologically similar in terms of rough texture, high magnetism, red or yellowish colour, and high corrosion or oxidation states. They have high ferro-magnetic property and heavier, probably because, during the production process, they were close or in contact with either iron or steel respectively.

Table 6.4: Smelting (SE) cake-like slags attributes. Note SD=standard deviation

S/No.	Site	Mass (kg)	Length (cm)	Width (cm)	Thickness (cm)
1	Itaka SE1	7	30	26	5
2	Itaka SE5	7	35	30	5
3	Itaka SE6	9	41	35	6
4	Kapoka SE1	8	26	21	6
5	Kapoka SE2	10	42	40	10
6	Kapoka SE3	12	34	30	5
7	Iyendwe SE1	15	43	38	6
8	Iyendwe SE2	16	45	41	9
9	Iyendwe SE3	17	40	34	8
10	Malolo SE1	8	41	37	7
11	Malolo SE2	15	50	46	10
12	Shihando SE1	10	36	30	5
13	Shihando SE2	11	42	40	6
14	Shihando SE3	12	47	40	6
15	**Average**	**11**	**39**	**35**	**7**
16	**SD**	**3**	**7**	**7**	**2**

Table 6.5: Refining (RF) cake-like slags attributes. Note SD = standard deviation

S/No.	Site	Mass (kg)	Length (cm)	Width (cm)	Thickness (cm)
1	Insane RF1	1.2	20	12	7
2	Insane RF2	0.6	12	10	5
3	Insane RF3	0.5	10	7	4
4	Itaka RF2	1	11	9	5
5	Itaka RF3	0.5	9	7	4
6	Itaka RF4	1	13	10	5
7	Malolo RF3A	1.5	9	7	4
8	Malolo RF3B	1	10	6	3
9	Shihando RF5	0.8	10	7	4
10	Shihando RF6	1	9	6	4
11	Shihando RF7	1	8	6	4
12	**Average**	**1**	**11**	**8**	**4**
13	**SD**	**0.3**	**3**	**2**	**1**

6.2.4.2 Smelting and refining (tap) flow slags

Table 6.6 and Table 6.7 present physical attributes of smelting and refining (tap) flow slags respectively. Based on the average and SD data, the smelting and refining (tap) flow slags are more or less similar in size and weight. Thus, like in Ufipa, macroscopic attributes of the tap or flow slags have limited use and cannot be used to differentiate the two processes.

Table 6.6: Smelting (SE) tap or flow slags attributes. Note SD=standard deviation

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Itaka SE1	77	12	4	2
2	Itaka SE5	56	6	4	2
3	Itaka SE6	59	10	3	2
4	Kapoka SE1	88	7	1	1
5	Kapoka SE2	105	8	3	1
6	Kapoka SE3	343	12	6	3
7	Iyendwe SE1	100	11	2	1
8	Iyendwe SE2	120	12	2	1
9	Iyendwe SE3	98	12	3	1
10	Malolo SE1	96	6	1	1
11	Malolo SE2	56	5	1	1
12	Shihando SE1	68	10	2	1
13	Shihando SE2	51	8	1	1
14	Shihando SE3	78	6	1	1
15	**Average**	**100**	**9**	**2**	**1**
16	**SD**	**73**	**3**	**2**	**1**

Table 6.7: Refining (RF) tap or flow slags attributes. Note SD = standard deviation

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Insane RF4	76	6	4	1
2	Insane RF5	53	5	3	1
3	Insane RF6	25	6	1	1
4	Itaka RF2	125	8	2	1
5	Itaka RF3	69	6	2	1
6	Itaka RF4	59	7	2	1
7	Malolo RF3A	115	9	5	2
8	Malolo RF3B	65	5	3	2
9	Shihando RF8	82	5	3	1
10	Shihando RF10	180	7	4	2
11	Shihando RF12	165	7	5	2
12	**Average**	**92**	**6**	**3**	**1**
13	**SD**	**48**	**1**	**1**	**1**

6.2.4.3 Smelting tuyère-mould slags from Mbozi

Tuyère-mould slags (Figure 6.5) in Unyiha are exclusively a characteristic of the ore smelting sites, indicating that slag was tapped through tuyères. They are absent at the refining sites, because slag was drained outside the *vintengwe* via a tunnel dug down slope. Based on Table 6.8 physical attributes, it is noticeable that the diameters of the tuyère-mould slags correspond to the average internal diameters of the tuyère pieces presented earlier.

Figure 6.5: Tuyère-mould slags from Unyiha smelting sites

Table 6.8: Smelting tuyère-mould slags attributes from Mbozi sites. Note SD=standard deviation

S/No.	Site	Mass (g)	Length (cm)	Width (cm)
1	Itaka SE1	60	7	3
2	Itaka SE5	65	6	3
3	Itaka SE5	65	6	3
4	Malolo SE2	50	5	3
5	Shihando SE1	107	5	4
6	Shihando SE8	30	3	3
7	Shihando SE9	90	7	3
8	Shihando SE9	148	10	4
9	Shihando SE9	70	7	3
10	**Average**	**76**	**6**	**3**
11	**SD**	**35**	**2**	**0.4**

6.2.4.4 Smithing slag attributes

The smithing slags were typically classified into (hammer) scales, (hollow) droplets, and agglomerated smithing slags. Based on this information, it is clear that smithing process can be differentiated from the smelting and refining processes in terms of the remains.

6.3 Presentation and Interpretation of Microscopic Data

6.3.1 Technical Ceramics Chemical Data

6.3.1.1 Technical ceramics of Itaka smelting site #1

Based on Table 6.9, on average, there is relatively more silica and soda but less alumina in the tuyères than in the furnace walls. In terms of the remaining major and minor oxides including trace oxides (Table 6.10), the tuyères and furnace wall samples are chemically similar (see Table 6.9) thus pointing towards a similar clay source, more likely termite mounds. The slight difference especially in silica can probably be

attributed to issues of preparation and production techniques or sampling of silica rich termite mounds possibly to enhance the thermal shock resistance of the tuyères (see Hein *et al*. 2007: 142), although it is difficult to verify whether this was an intentional decision. However, it appears that refractory quality of about 1600 ^{o}C (maximum) of the two ceramics was not affected by the sampling problems (Figure 6.6).

Table 6.9: (P) XRF-EDS Major and minor oxide concentrations (in wt%) of technical ceramics from Itaka smelting site #1. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 6.7, FW=furnace wall, and TYR=tuyère

S/No.	Sample /Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
1	1FW1	0.29	0.28	29.29	56.71	0.03	1.37	0.21	1.70	0.02	0.25	9.85	92.32
2	1FW2	0.28	0.23	30.86	55.42	0.04	1.18	0.19	1.65	0.03	0.21	9.91	92.00
3	1FW3	0.29	0.24	32.11	53.37	0.07	1.34	0.19	1.72	0.03	0.22	10.43	91.94
4	1TYR1	0.53	0.30	25.56	60.90	0.02	1.70	0.36	1.66	0.02	0.32	8.63	91.95
5	1TYR2	0.31	0.25	28.11	57.88	0.02	1.22	0.23	1.72	0.02	0.22	10.00	92.53
6	1TYR3	0.39	0.18	28.13	59.02	0.04	1.52	0.26	1.61	0.02	0.25	8.58	91.80

Table 6.10: (P) XRF-EDS Trace element concentrations (in ppm) of the technical ceramics from Itaka smelting site #1. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 6.8, FW=furnace wall, and TYR=tuyère

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	WO_3	PbO	Th
1	1FW1	78	18	31	71	19	51	16	20	336	121	57	23	82	50	18	27
2	1FW2	94	11	24	67	20	46	16	21	331	118	57	24	83	20	19	26
3	1FW3	84	16	24	71	21	55	17	21	361	134	64	23	90	5	21	29
4	1TYR1	71	11	27	74	18	58	23	20	349	122	64	25	86	56	20	27
5	1TYR2	84	15	35	68	19	50	16	21	338	121	59	25	89	51	19	26
6	1TYR3	65	10	21	71	18	52	21	21	350	124	60	23	81	16	21	29

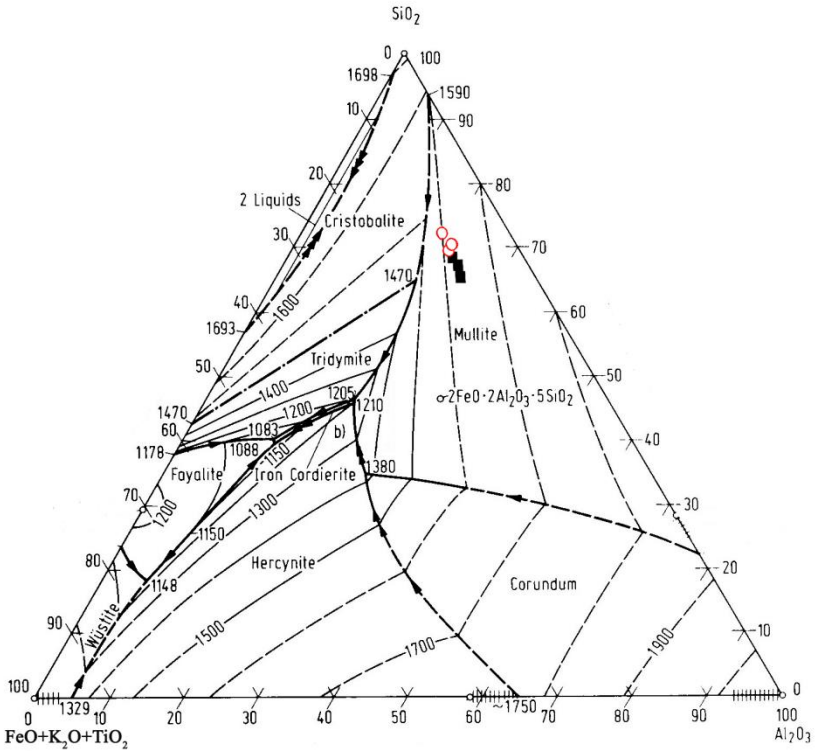

Figure 6.6: Al_2O_3-SiO_2-FeO phase diagram for the furnace walls (black squares) and tuyères (red circles) from Itaka smelting site #1

6.3.1.2 Technical ceramics of Itaka refining site #2

On average, the three sets of ceramics are not similar; although the furnace walls seem to be more related to the potsherds than to the tuyères (see Table 6.11). This indicates that possibly the sets were collected from different clay sources, apparently with different maximum refractory quality (see Figure 6.7). It is more likely that the furnace walls were made from termite mound clay that I observed next to the site, while the relatively increased concentration of silica in the tuyères suggests that its sources may have been external to the termite mound clay. The smelters, through repeated experience, might have been aware of the fact that silica in terms of quartz improves the refractory quality of clays (Freestone and Tite 1986), because tuyères were subjected to relatively more heat than the furnace walls. The

proposition of different sources of clays for the ceramics is supported by differences in the concentration of trace oxides as well (see Table 6.12).

Table 6.11: (P) XRF-EDS Major and minor element concentrations (in wt%) of technical ceramics from Itaka smelting site #2. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 6.9, FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
1	2FW1	0.32	0.20	30.21	55.97	0.04	1.57	0.19	1.60	0.02	0.14	9.73	91.99
2	2FW2	0.40	0.21	28.91	57.66	0.05	1.70	0.21	1.59	0.02	0.22	9.04	91.80
3	2FW3	0.31	0.27	29.07	56.40	0.03	1.46	0.18	1.68	0.02	0.22	10.35	92.50
4	2TYR1	0.73	1.96	19.63	65.33	0.01	2.05	2.55	0.70	0.02	0.06	6.96	91.32
5	2TYR2	0.93	1.91	20.28	63.81	0.01	1.49	1.17	0.94	0.02	0.09	9.35	91.28
6	2TYR3	0.70	1.90	19.92	65.11	0.01	2.11	2.50	0.71	0.01	0.09	6.94	91.40
7	2PTR1	0.30	0.23	27.33	58.77	0.03	1.23	0.22	1.75	0.02	0.24	9.87	92.71
8	2PTR2	0.51	0.27	23.50	61.76	0.02	1.50	0.30	2.10	0.02	0.35	9.68	92.92
9	2PTR3	0.50	0.27	24.71	60.15	0.03	1.71	0.39	1.98	0.02	0.33	9.89	92.78

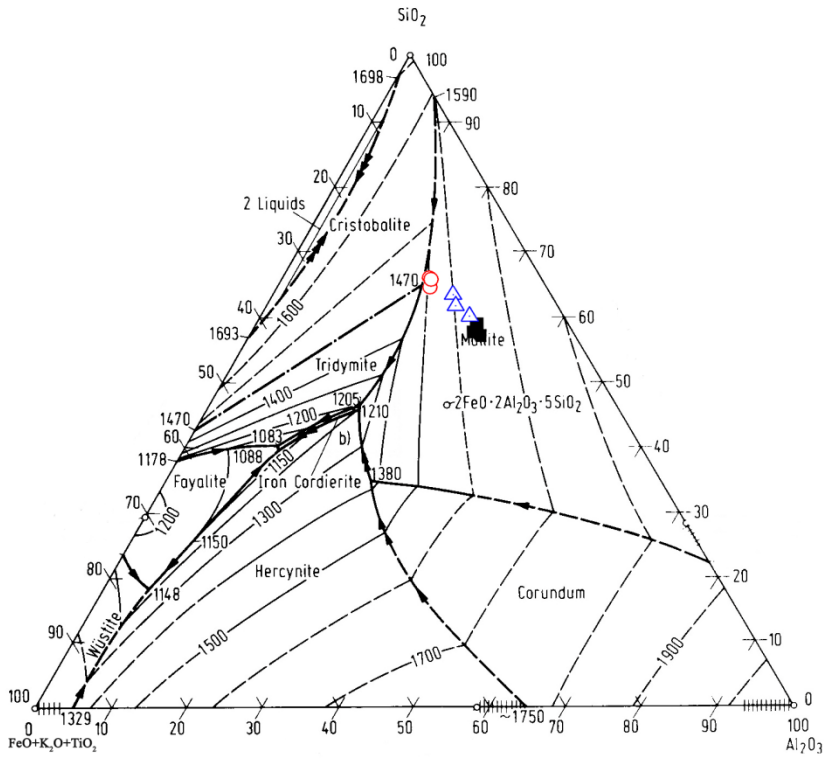

Figure 6.7: Al_2O_3-SiO_2-FeO phase diagram for the furnace walls, tuyères, and potsherds from Itaka2 refining site. Note that the circles (red) are the tuyères, the triangles (blue) are the potsherds, and the squares (black) are the furnace wall samples

Table 6.12: (P) XRF-EDS Trace elements concentration (in ppm) of the technical ceramics from Itaka smelting site #2. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 6.10, FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	WO_3	PbO	Th
1	2FW1	83	13	25	66	20	48	19	24	361	117	84	25	90	7	21	31
2	2FW2	86	13	23	72	20	48	21	23	355	121	82	24	90	9	24	28
3	2FW3	100	16	30	81	21	53	16	21	358	123	81	24	91	44	17	29
4	2TYR1	53	8	26	45	10	47	110	17	72	7	191	14	13	39	9	9
5	2TYR2	71	30	63	46	13	39	71	16	120	30	94	17	34	68	8	10
6	2TYR3	55	10	26	43	11	47	111	16	64	7	190	13	21	27	9	9
7	2PTR1	84	15	40	76	20	50	17	21	342	127	58	29	94	45	20	27
8	2PTR2	83	11	27	76	18	57	20	23	340	116	70	29	92	72	20	27
9	2PTR3	82	14	40	82	18	64	22	23	332	117	64	28	84	36	17	27

6.3.2 Slag Chemical Data

In order to differentiate smelting from refining slags, I predicted that because the smelted impure iron pieces and charcoal alone were charged in the *vintengwe* (e.g. Brock and Brock 1965), the reduction or rather complete chemical separation of the impurities (slags and charcoal) from iron would decrease FeO concentration and increase the concentration of the other slag oxides per unit volume. This prediction is examined in the light of slag chemical composition data from three sets of smelting and refining sites.

6.3.2.1 Smelting and refining slag chemical data from Malolo sites

On average, the FeO concentration increased to 49 wt% in the refining slags from about 32 wt% in the smelting slag (Table 6.13). The increase can be attributed to the unavoidable addition of iron metal droplets (see mineralogy section) in the refining slag, because they were close or in contact with the final products (see Rehren and Ganzelewski 1995; Miller and Killick 2004). Excluding silica and titania oxides, which were not affected, possibly due to incorporation of extra silica and titania in the refining process; the increase of iron oxide concentration unsurprisingly diluted the concentration of alumina, manganese, potash, lime, soda, phosphate, barium, magnesia, and cerium oxides per unit volume (see Table 6.13).

It also lowered the concentration of most of the trace oxides, but it is noteworthy that depending on how much they picked up in the process or during slag tapping, some including zirconium, praseodymium, and uranium oxides were not affected, and yet cobalt and copper oxides concentration slightly increased (Table 6.14).

Table 6.13: SEM-EDS major and minor oxide concentrations (in wt%) of the smelting (SE) and refining (RF) slags from Malolo sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 6.11

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	BaO	Ce_2O_3	Total
1	1SE1	0.6	0.3	13.3	31.3	0.9	1.4	2.3	0.6	6.2	42.5	0.5	0.0	100
2	1SE2	0.7	0.2	13.3	28.4	0.9	1.6	1.8	0.7	3.4	48.5	0.4	0.1	100
3	1SE3	0.9	0.4	14.5	31.5	1.0	2.2	2.4	0.6	26.1	19.9	0.4	0.1	100
4	1SE4	1.2	0.6	18.6	39.3	0.5	3.4	2.7	0.8	12.8	20.1	0.0	0.2	100
5	1SE5	1.3	0.4	14.6	32.9	0.3	2.5	2.7	0.5	16.0	28.5	0.1	0.1	100
6	3BRF1	0.3	0.2	12.0	39.1	0.2	0.6	0.5	1.2	1.1	44.6	0.1	0.2	100
7	3BRF2	0.3	0.1	11.2	41.9	0.2	0.6	0.4	1.1	1.0	42.8	0.2	0.1	100
8	3BRF3	0.8	0.2	14.3	24.8	0.7	1.3	1.0	0.5	2.9	53.1	0.2	0.1	100
9	3BRF4	0.3	0.2	13.4	20.2	0.6	1.0	1.3	0.4	1.9	60.6	0.3	0.0	100
10	3BRF5	0.3	0.1	12.0	38.4	0.1	0.6	0.4	1.1	1.1	45.8	0.3	0.0	100

Table 6.14: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Malolo sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 6.12

S/No.	Sample/ Oxides	Co_3O_4	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	La	Pr	Nd	Ta_2O_5	WO_3	U
1	1SE1	120	16	71	88	31	208	89	23	15	21	15	19	12
2	1SE2	130	16	64	74	47	296	144	31	15	21	11	38	18
3	1SE3	86	10	28	144	76	213	124	88	15	50	9	40	12
4	1SE4	76	9	49	104	70	273	168	91	13	52	11	59	12
5	1SE5	99	9	40	163	58	213	125	71	13	19	14	21	15
6	3BRF1	149	31	20	24	19	278	98	7	14	20	15	16	11
7	3BRF2	133	43	27	21	19	277	98	8	14	20	12	229	12
8	3BRF3	130	10	59	50	29	249	112	19	14	20	12	17	14
9	3BRF4	153	14	40	43	22	215	102	16	14	20	17	22	11
10	3BRF5	165	29	20	23	18	259	95	7	13	19	16	17	12

6.3.2.2 Smelting and refining slag chemical data from Shihando sites

Like the chemical composition of samples from Malolo, on average, there is relatively higher FeO concentration of about 36 wt% in the refining slags than in the smelting

slags, with about 30 wt% FeO (see Table 6.15). As might be expected, the increase in FeO concentration per unit volume, assuming other factors were kept constant, diluted the concentration of the rest of the major and minor oxides. In addition, the concentration of trace oxides such as strontium, yttrium, zinc, and neodymium were lowered, although some show no systematic differences across the sites (see Table 6.16). It was difficult during pre-industrial iron/steel production process to 100 % separate slag from the metal, without losing some iron (droplets) into the slags (see mineralogical data). This might have been even more difficult for the refining process, because the smelted (impure) iron was already in contact with the smelting slags, which can explain why there is more FeO in the refining slags than in the smelting slags (similarly, fining slags elsewhere have relatively higher concentration of FeO, see also Killick and Gordon 1987; Rehren and Ganzelewski 1995).

Table 6.15: SEM-EDS major and minor oxide concentrations (in wt%) of the smelting (SE) and refining (RF) slags from Shihando sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 6.13. Note higher concentration for Ce_2O_3 and see Appendix 6.14 for details

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	BaO	Ce_2O_3	Total
1	9SE1	1.4	0.4	13.0	39.5	0.3	2.7	3.1	0.8	5.0	33.5	0.1	0.1	100
2	9SE2	1.2	0.7	11.4	38.0	0.4	3.0	3.7	0.8	4.5	36.2	0.1	0.1	100
3	9SE3	1.5	0.8	15.1	43.2	0.3	2.7	3.2	0.9	11.5	19.6	0.8	0.3	100
4	9SE4	1.0	0.5	13.2	38.0	0.5	2.0	2.0	0.7	7.3	33.9	0.7	0.1	100
5	9SE5	0.8	0.6	13.8	37.7	0.5	2.0	3.5	1.1	11.0	28.3	0.6	0.2	100
6	7RF3	1.1	0.0	13.2	36.3	0.2	1.9	1.0	0.6	8.5	36.6	0.3	0.3	100
7	7RF5	1.4	0.3	11.6	39.7	0.2	2.1	1.0	0.6	7.3	35.4	0.3	0.2	100
8	7RF6	1.2	0.2	11.8	39.3	0.3	1.7	1.1	0.6	7.1	36.5	0.3	0.1	100
9	7RF7	1.4	0.1	11.5	41.3	0.2	2.0	0.8	0.8	6.5	35.1	0.1	0.1	100
10	7RF8	1.3	0.3	13.0	36.5	0.3	1.9	0.8	0.6	9.0	35.7	0.4	0.5	100

Table 6.16: (P) XRF-EDS Trace oxides concentration (in ppm) of the smelting (SE) and refining (RF) slags from Shihando sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 6.15

S/No.	Sample/ Oxides	Co_3O_4	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	La	Pr	Nd	Ta_2O_5	WO_3	U
1	9SE1	100	11	32	124	36	215	124	37	13	19	14	41	9
2	9SE2	98	13	36	121	36	214	116	36	13	19	13	25	11
3	9TSE3	63	10	51	146	54	277	155	79	13	60	16	63	10
4	9SE4	100	9	64	103	33	239	120	35	15	35	14	50	13
5	9SE5	94	13	25	171	50	272	149	66	14	56	11	18	12
6	7RF3	110	16	32	64	43	236	138	60	14	38	9		
7	7RF5	100	10	31	63	42	221	121	48	14	20	12	76	13
8	7RF6	110	18	30	58	38	208	118	51	15	26	10	73	11
9	7RF7	100	19	46	58	44	241	131	48	13	19	14	20	15
10	7RF8	110	17	34	63	43	231	129	63	14	38	12	32	10

6.3.2.3 Smelting and refining slag chemical data from Itaka sites

Like the samples from Malolo and Shihando areas, on average, there is relatively higher FeO concentration of about 38 wt% in the refining slags than in the smelting slags with about 34 wt% FeO (Table 6.17). Likewise the increased concentration of FeO in the refining slags possibly due to unavoidable loss of FeO in the slags consequently diluted and lowered the concentration of silica, manganese, potash, lime, soda, barium, magnesia, phosphate, and cerium oxides, although alumina slightly increased in concentration from 12-13 wt% in the smelting and refining slags respectively (see Table 6.17). One can propose that the slight increase of alumina concentration in the refining slags could have been accidental addition from the furnace wall or anywhere in the iron refining system. Also, the increased concentrations of FeO and Al_2O_3 in the refining slags expectedly lowered the concentration of trace oxides including niobium, strontium, lanthanum, yttrium, zinc, and neodymium, although the rest of the trace oxides were not affected, and the concentration of cobalt slightly increased in the

refining slags (Table 6.18), depending on how much of these were accidentally picked up in the refining system.

Table 6.17: SEM-EDS major and minor oxide concentrations (in wt%) of the smelting (SE) and refining (RF) slags from Shihando sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 6.16

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	BaO	Ce_2O_3	Total
1	1SE1	1.2	0.4	11.3	41.4	0.3	1.9	1.6	0.7	3.9	36.9	0.3	0.2	100
2	1SE2	1.2	0.4	12.3	39.4	0.5	2.1	1.8	0.7	3.4	37.7	0.4	0.2	100
3	1SE3	1.1	0.3	13.8	33.6	0.4	1.9	1.5	0.6	17.9	27.5	1.4	0.1	100
4	1SE4	1.3	0.5	13.1	40.9	0.5	2.5	2.5	0.7	9.0	28.8	0.3	0.1	100
5	1SE5	1.2	0.4	11.0	40.3	0.4	1.8	1.4	0.7	3.8	38.8	0.1	0.2	100
6	2RF3	0.6	0.2	11.7	34.2	0.5	1.2	1.2	1.1	3.7	45.2	0.4	0.1	100
7	2RF4	1.5	0.2	13.2	39.5	0.1	2.0	0.8	0.7	7.0	34.4	0.3	0.3	100
8	2RF5	1.0	0.3	14.1	36.4	0.3	1.8	0.9	0.8	8.3	35.3	0.5	0.1	100
9	2RF6	1.4	0.3	12.7	37.1	0.1	1.7	1.1	0.8	6.7	37.7	0.3	0.2	100
10	2RF7	1.5	0.2	13.2	36.6	0.2	1.9	1.1	0.7	6.4	37.5	0.4	0.2	100

Table 6.18: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Shihando sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 6.17

S/No.	Sample/ Oxides	Co_3O_4	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	La	Pr	Nd	Ta_2O_5	WO_3	U
1	1SE1	100	9	32	57	40	225	132	48	14	20	12	45	14
2	1SE2	100	10	26	78	32	252	134	29	14	20	22	13	14
3	1SE3	99	7	65	156	44	229	137	52	17	51	13	22	13
4	1SE4	96	10	32	118	38	219	122	43	14	19	10	39	9
5	1SE5	100	9	32	52	37	209	121	41	13	26	15	21	9
6	2RF3	120	15	30	70	31	259	126	27	14	20	15	32	11
7	2RF4	100	9	34	63	38	222	121	44	14				
8	2RF5	110	13	31	77	40	227	127	50	15	39	11	52	14
9	2RF6	110	10	27	59	37	209	121	47	14	30	14	29	11
10	2RF7	110	8	24	60	37	204	122	46	14	31	14	20	13

To sum up on the chemical data, semi-bulk area results (Appendix 6.18 through 6.20) excluding metal inclusions and unreacted materials are used to estimate the slags melting temperatures (Figure 6.8). The proposed chemical differences between smelting and refining slags from the three villages is virtually apparent (see Figure 6.8), with relatively more FeO in the refining slags and less FeO in the smelting slags, although some samples overlap. Both processes were technically efficient, because the samples cluster into the Optimum 1 efficient zone (see Rehren *et al*. 2007).

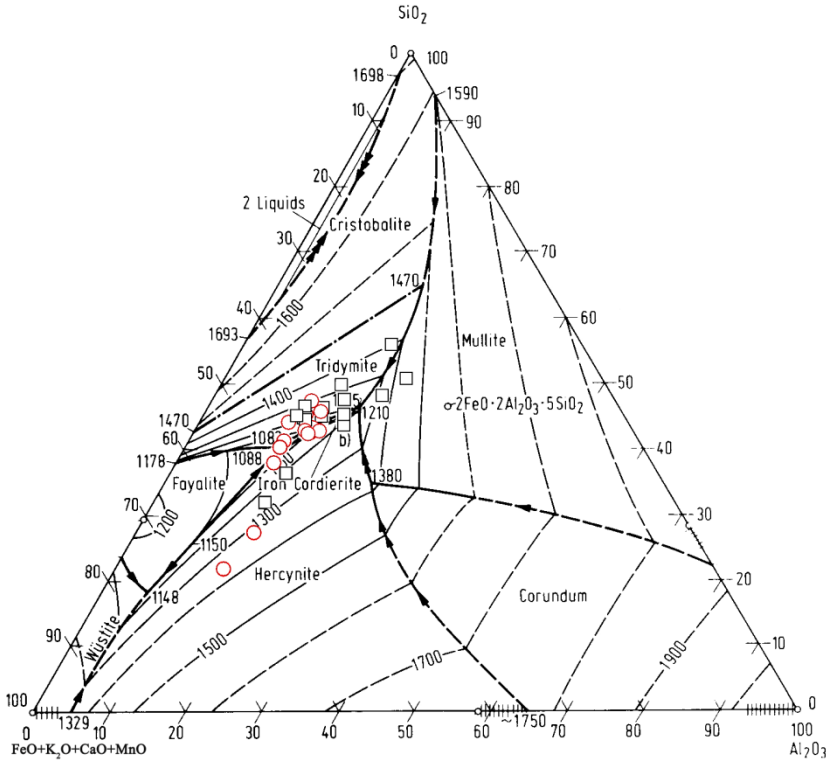

Figure 6.8: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting (black squares) and refining (red circles) slags from Malolo, Shihando, and Itaka sites

6.3.3 Slag Mineralogical Data

Table 6.19 presents a summary of all the crystals identified in both smelting and refining slags from Mbozi. For the sake of clarity, each of the phases, fayalite through quartz, is examined alone in terms of frequency, microstructure, purity, and its

technological implications. The purpose of this was to compare the technology of the three villages.

Table 6.19: Summary of the crystals of smelting and refining slags from Mbozi sites

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Magnetite	Tap line	Wüstite	Fe Droplets	Angular Fe	Porosity	Quartz
Smelting and refining slags from Malolo											
1	1SE1	√	√	√	–	√	–	–	√	√	√
2	1SE2	√	√	√	–	–	–	–	√	√	–
3	1SE3	√	√	√	–	–	–	–	√	√	–
4	1SE4	√	√	√	–	–	–	–	√	√	√
5	1SE5	√	√	√	√	–	–	–	–	√	√
6	3BRF1	√	–	√	–	–	–	√	–	√	–
7	3BRF2	√	–	√	–	–	–	√	–	√	–
8	3BRF3	√	√	√	–	√	–	√	–	√	–
9	3BRF4	√	√	√	√	–	√	√	–	√	–
10	3BRF5	√	–	√	–	√	–	√	–	√	–
Smelting and refining slags from Shihando											
11	9SE1	√	–	√	–	–	–	–	–	√	–
12	9SE2	√	–	√	–	√	–	–	–	√	√
13	9SE3	√	√	√	–	–	–	–	√	√	√
14	9SE4	√	√	√	–	–	–	–	–	√	√
15	9SE5	√	√	√	–	–	–	–	–	√	√
16	7RF3	√	–	√	–	–	–	√	–	√	√
17	7RF5	√	–	√	–	–	–	√	–	√	–
18	7RF6	√	–	√	–	–	–	√	–	√	√
19	7RF7	√	–	√	–	–	–	√	–	√	–
20	7RF8	√	–	√	–	–	–	√	–	√	√
Smelting and refining slags from Itaka											
21	1SE1	√	–	√	–	–	–	–	–	√	–
22	1SE2	√	–	√	–	–	–	–	–	√	–
23	1SE3	√	√	√	–	√	–	–	√	√	–
24	1SE4	√	√	√	–	√	–	–	√	√	√
25	1SE5	√	–	√	–	–	–	–	–	√	√
26	2RF3	√	√	√	–	–	–	√	–	√	√
27	2RF4	√	–	√	–	–	–	√	–	√	√
28	2RF5	√	–	√	–	–	–	√	–	√	√
29	2RF6	√	–	√	–	–	–	√	–	√	–
30	2RF7	√	–	√	–	–	–	√	–	√	√

6.3.3.1 Fayalite crystals

Fayalite was found in all smelting and refining slag samples as a dominant phase (see Table 6.19). The crystals are skeletal, thin, and elongated (Figure 6.9) indicative of slag tapping practise for the *malungu* and *vintengwe* furnaces (see Brock and Brock 1965: 98). Based on the chemical composition of the slags (Table 6.20), some of the crystals are pure fayalite, with a $2FeO.SiO_2$ chemistry, while others are impure fayalitic crystals with a $2(Fe.Mn)O.SiO_2$ formula. The presence of manganese in the crystals is the result of the use of Mn-rich ores, and according to Bachmann (1982: 14), the latter crystals are referred to as knebelite. It is noted that sample 3BRF2 was an impure crystal, probably a mix of fayalite and hercynite. As well as the major components, the fayalite and knebelite crystals constituted MgO, Al_2O_3, P_2O_5, K_2O, CaO, and TiO_2 oxides, although in small concentration (see Table 6.20).

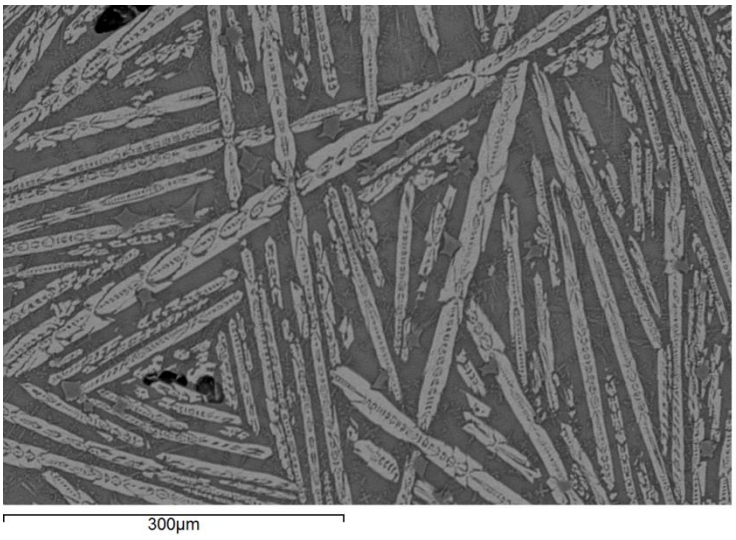

Figure 6.9: SEM-BSE image of the skeletal fayalitic crystals, sample Itaka2 RF3. Note hercynite (angular dark grey), glass matrix (dark grey), and porosity (black).

Table 6.20: SEM-EDS chemical composition (in wt%) of fayalitic crystals in the smelting (SE) and refining (RF) slags from Mbozi. Note the results are the average of three spectra and are normalised to 100 wt%; the full results in Appendix 6.21

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
Smelting and refining slags from Malolo											
1	1SE1	0.6	0.2	30.3	0.2	0.1	0.3	0.1	9.8	58.5	100
2	1SE2	0.7	0.2	30.4	0.1	0.0	0.4	0.1	5.5	62.6	100
3	1SE3	0.7	0.2	30.2	0.4	0.0	0.3	0.1	39.4	28.8	100
4	1SE4	1.2	0.5	31.5	0.2	0.2	0.3	0.2	26.8	39.0	100
5	1SE5	1.5	0.2	30.8	0.1	0.0	0.9	0.1	26.6	39.7	100
6	3BRF1	0.5	0.5	30.9	0.2	0.0	0.1	0.5	1.1	66.3	100
7	3BRF2	0.1	11.8	42.3	0.1	0.7	0.4	1.3	1.1	42.2	100
8	3BRF3	0.5	0.5	29.4	0.3	0.0	0.2	0.2	4.4	64.4	100
9	3BRF4	0.5	0.4	30.1	0.4	0.0	0.5	0.1	3.1	64.9	100
10	3BRF5	0.4	0.3	30.0	0.0	0.0	0.0	0.3	1.7	67.2	100
Smelting and refining slags from Shihando											
11	9SE1	2.1	0.5	31.9	0.1	0.2	0.6	0.1	8.5	56.1	100
12	9SE2	2.0	0.5	30.6	0.1	0.2	0.6	0.1	6.7	59.1	100
13	9SE3	1.9	0.3	31.3	0.1	0.1	0.5	0.2	25.4	40.1	100
14	9SE4	1.0	0.2	31.1	0.2	0.1	0.2	0.2	11.6	55.4	100
15	9SE5	2.8	0.1	31.1	0.1	0.0	0.4	0.1	20.3	45.1	100
16	7RF3	0.5	0.4	30.4	0.0	0.0	0.2	0.1	12.4	55.8	100
17	7RF5	0.7	0.8	32.3	0.0	0.3	0.3	0.3	10.7	54.7	100
18	7RF6	0.5	0.2	31.1	0.2	0.0	0.1	0.2	10.2	57.4	100
19	7RF7	0.7	0.2	30.7	0.1	0.1	0.1	0.1	9.7	58.2	100
20	7RF8	0.6	0.3	30.0	0.0	0.0	0.1	0.2	13.6	55.1	100
Smelting and refining slags from Itaka											
21	1SE1	1.3	0.2	31.4	0.1	0.1	0.2	0.2	6.1	60.5	100
22	1SE2	1.3	0.2	31.5	0.1	0.1	0.2	0.1	4.8	61.6	100
23	1SE3	0.9	0.2	31.2	0.1	0.0	0.2	0.2	28.9	38.3	100
24	1SE4	1.8	0.5	31.2	0.3	0.1	0.4	0.2	11.2	54.3	100
25	1SE5	0.7	2.0	33.4	0.1	0.5	0.4	0.3	4.9	57.8	100
26	2RF3	1.0	0.2	30.4	0.4	0.0	0.1	0.2	4.4	63.2	100
27	2RF4	0.8	0.3	31.5	0.1	0.0	0.1	0.1	9.9	57.2	100
28	2RF5	0.9	0.3	30.8	0.3	0.1	0.1	0.2	12.9	54.3	100
29	2RF6	0.6	0.2	30.7	0.1	0.0	0.1	0.2	10.2	58.0	100
30	2RF7	0.7	0.4	30.3	0.1	0.0	0.1	0.2	10.2	58.0	100

6.3.3.2 Hercynite crystals

Of all samples (n=30), 14 samples had hercynite crystals (Table 6.21). On the basis of 1 molecule of each FeO and Al_2O_3 oxides virtually all the crystals were pure (Figure 6.10), although 4 samples including 1SE3 and 1SE5 from Malolo, 9RF5 from Shihando, and 1SE3 from Itaka had relatively less FeO concurrently with elevated concentration of MnO (see Table 6.21). It can be argued that there were relatively less atoms of Fe^{2+} but more atoms of Al^{3+} in the melt to form proper hercynite when the crystals started forming, where the excess Al^{3+} had to combine with freely available Mn^{2+} in the melt to form such less pure crystals. Accordingly, few samples including 9SE4 had crystals with excess iron oxide, because there was possibly more Fe^{3+} in the melt with less Al^{3+} when hercynite was forming. Hercynite could not chemically accommodate the extra iron oxide (Fe^{3+}), and as a result, the excess Fe^{3+} accumulated and cooled surrounding the hercynite proper (Figure 6.11; Figure 6.12), forming zoned hercynite crystals (see Bachmann 1982: 16; Killick and Gordon 1987: 32). As well as FeO, MnO, and Al_2O_3 concentrations, on average, the crystals constitute MgO, SiO_2, TiO_2, V_2O_5, and Cr_2O_3 oxides (see Table 6.21).

Table 6.21: SEM-EDS chemical composition (in wt%) of hercynitic crystals in the smelting (SE) and refining (RF) slags from Mbozi. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	K_2O	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
Smelting and refining slags from Malolo											
1	1SE1	1.0	51.4	0.3	0.0	0.6	0.3	0.1	4.1	42.3	100
2	1SE2	0.4	51.3	0.2	0.1	0.5	0.3	0.0	1.8	45.4	100
3	1SE3	0.7	52.4	0.3	0.0	0.7	0.1	0.0	19.4	26.3	100
4	1SE4	1.2	55.9	0.2	0.1	0.3	0.2	0.2	9.9	32.0	100
5	1SE5	2.1	52.4	0.2	0.0	0.3	0.1	0.1	14.2	30.6	100
6	3BRF3	0.5	53.8	0.1	0.0	0.5	0.3	0.1	1.7	43.1	100
7	3BRF4	0.6	53.0	0.2	0.0	0.3	0.2	0.0	1.1	44.5	100
Smelting and refining slags from Shihando											
8	9SE3	1.5	48.7	0.3	0.1	1.3	0.7	0.3	9.5	37.6	100
9	9SE4	0.5	41.8	0.8	0.2	1.5	0.5	0.5	3.9	50.4	100
10	9SE5	1.8	44.3	0.2	0.0	1.1	0.3	0.3	17.6	34.3	100
Smelting and refining slags from Itaka											
11	1SE3	0.5	51.2	0.3	0.0	1.0	0.3	0.1	11.3	35.1	100
12	1SE4	1.0	47.0	1.2	0.1	1.5	1.0	0.6	4.2	43.6	100
13	2RF3	0.4	47.3	0.4	0.0	1.7	0.9	1.3	1.8	46.1	100
14	2RF5	0.6	49.9	1.1	0.2	1.6	0.9	0.5	5.2	40.1	100

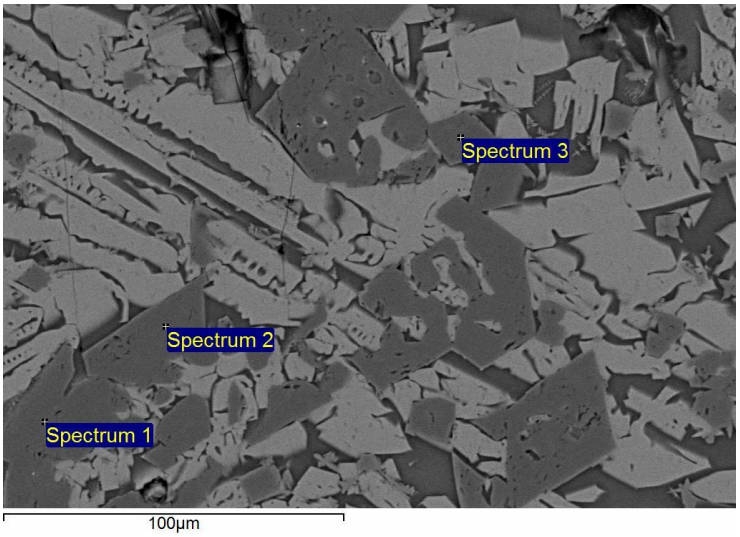

Figure 6.10: SEM-BSE image of pure hercynite crystals, Malolo1 SE2. Note fayalite (grey), glass matrix (dark grey), and porosity (black)

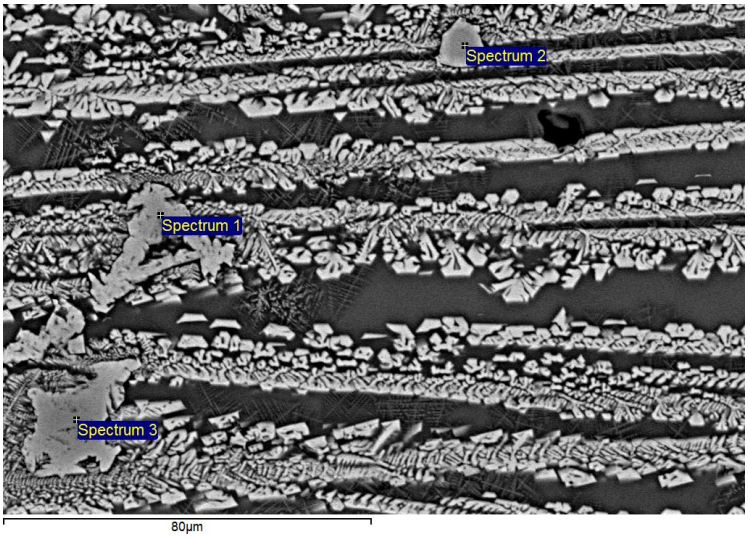

Figure 6.11: SEM-BSE image of impure (or zoned) hercynite crystals, sample Shihando9 SE4. Note fayalite (grey), glass matrix (dark grey), and porosity (black).

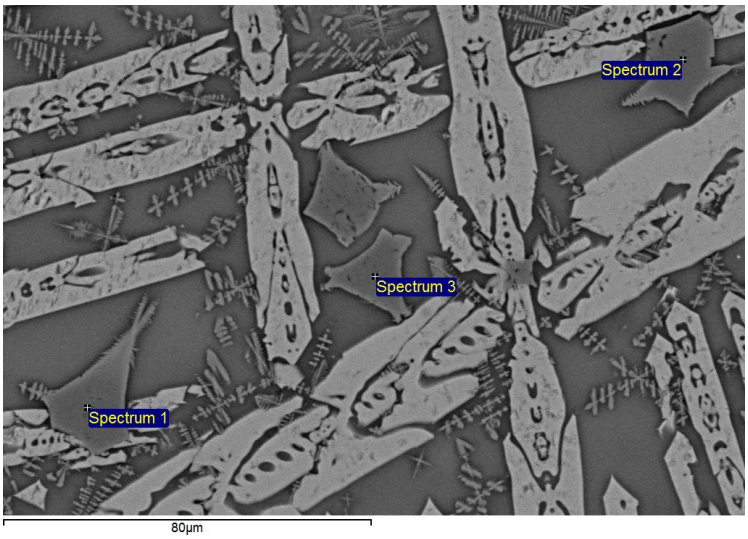

Figure 6.12: SEM-BSE image of zoned hercynite crystals. Note that the core (dark) is rich in alumina, and the outer (bright) is rich in iron oxides, sample Itaka1 SE3. Note fayalite (grey), glass matrix (dark grey), and porosity (black)

6.3.3.3 Glass groundmass

Glass groundmass on average constituted SiO_2, FeO, Al_2O_3, and MnO, CaO, K_2O, Na_2O, TiO_2, BaO, Ce_2O_3, and P_2O_5 oxides (see Table 6.22). Interestingly, there is a systematic increase in FeO concentration in glass groundmass coupled with a decreased concentration of the other oxides in the refining samples, except that the alumina concentration slightly increased for the Shihando and Itaka refining sites, from 18 to 19

wt%. This can be explained; there were probably excess iron oxides (Fe^{2+} and Fe^{3+}) in the refining system that went into the glass after the formation of the other slag phases. Also, when compared to the fayalite and hercynite phases, the glass phase is evidently rich in fuel ash oxides including lime, potash, soda, and phosphate, because they were unable to form the other phases.

Table 6.22: SEM-EDS chemical composition (in wt%) of glass groundmass in the smelting (SE) and refining (RF) slags from Mbozi. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Na_2O	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	MoO_3	BaO	Ce_2O_3	Total
Smelting and refining slags from Malolo														
1	1SE1	1.8	18.5	46.8	2.5	4.8	7.2	1.1	1.8	13.0	0.0	2.1	0.2	100
2	1SE2	1.8	16.3	39.8	2.5	5.1	7.0	0.9	1.5	22.9	0.0	1.5	0.5	100
3	1SE3	1.1	20.0	36.6	1.5	3.8	5.3	1.0	16.4	12.7	0.4	1.1	0.1	100
4	1SE4	1.6	21.3	44.9	0.3	3.3	3.9	0.8	9.6	13.6	0.2	0.2	0.3	100
5	1SE5	1.5	15.6	40.7	0.8	4.1	7.7	0.7	9.7	18.4	0.0	0.4	0.4	100
6	3BRF1	0.1	18.8	44.0	0.2	0.9	0.8	1.7	0.9	32.4	0.0	0.3	0.0	100
7	3BRF2	0.2	11.7	41.3	0.1	0.6	0.5	1.2	1.0	43.2	0.2	0.1	0.0	100
8	3BRF3	2.7	16.4	37.2	3.0	6.3	7.0	0.6	1.0	23.5	0.0	0.9	0.7	100
9	3BRF4	1.6	17.5	37.5	2.7	7.3	10.4	0.4	0.6	19.9	0.0	1.2	0.4	100
10	3BRF5	0.2	14.0	40.5	0.1	0.6	0.6	1.4	1.2	41.0	0.1	0.3	0.0	100
Smelting and refining slags from Shihando														
11	9SE1	1.7	18.3	45.3	0.6	3.6	8.4	0.9	2.7	17.6	0.0	0.2	0.4	100
12	9SE2	2.0	20.5	44.5	0.5	4.5	7.5	1.0	1.8	16.7	0.2	0.3	0.2	100
13	9SE3	1.6	20.1	50.1	0.3	2.6	4.1	1.5	8.0	9.1	0.7	1.2	0.9	100
14	9SE4	1.1	17.5	45.0	0.6	2.2	4.6	0.9	5.6	20.7	0.0	1.3	0.2	100
15	9SE5	0.7	17.6	42.2	0.6	2.5	6.0	1.5	8.5	18.9	0.1	0.9	0.2	100
16	7RF3	1.3	20.2	40.8	0.3	2.5	1.4	0.9	6.3	25.6	0.0	0.5	0.5	100
17	7RF5	1.6	20.0	46.6	0.2	2.8	2.0	1.3	4.7	20.3	0.0	0.4	0.3	100
18	7RF6	2.0	21.6	44.7	0.2	2.4	3.6	1.2	4.8	17.8	0.2	0.6	0.7	100
19	7RF7	1.8	17.9	47.1	0.2	2.5	1.4	1.4	4.2	22.9	0.2	0.3	0.2	100
20	7RF8	1.5	18.7	39.7	0.3	2.5	1.4	0.9	6.6	27.3	0.3	0.5	0.5	100
Smelting and refining slags from Itaka														
21	1SE1	1.6	18.8	48.2	0.4	2.7	2.5	1.1	2.5	21.4	0.4	0.4	0.2	100
22	1SE2	1.6	13.7	48.5	0.5	2.8	3.9	0.7	2.1	24.8	0.2	0.5	0.6	100
23	1SE3	1.5	20.5	39.3	0.4	2.5	3.3	1.2	11.0	17.8	0.1	1.8	0.4	100
24	1SE4	1.7	19.9	45.1	0.9	2.9	7.3	1.1	3.6	16.3	0.1	0.5	0.5	100
25	1SE5	1.6	17.9	46.4	0.5	2.2	2.3	1.1	2.4	24.9	0.0	0.4	0.2	100
26	2RF3	0.7	16.5	40.8	0.4	1.5	1.6	1.8	3.5	32.6	0.0	0.4	0.2	100
27	2RF4	1.5	18.1	42.8	0.2	2.4	1.3	1.1	4.8	26.8	0.1	0.6	0.3	100
28	2RF5	1.2	20.6	42.9	0.4	2.5	2.4	1.4	6.2	21.0	0.0	0.9	0.4	100
29	2RF6	1.7	18.0	41.2	0.3	2.5	1.5	1.2	4.9	28.0	0.0	0.5	0.5	100
30	2RF7	2.1	20.7	42.6	0.2	2.8	1.7	1.2	4.3	23.0	0.4	0.7	0.4	100

6.3.3.4 Tap lines

Tap lines or magnetite skins are characteristic of the smelting (Figure 6.13) and refining (Figure 6.14) slags. This is a strong evidence for slag tapping technology, because they formed by oxidation through contact with ambient air while slag flowed outside the furnace. The presence of tap lines in the slags confirms the ethnoarchaeological, archaeological (smelting tuyère-mould slags, for example), and mineralogical (thin crystals) data for the practice of slag tapping in this area.

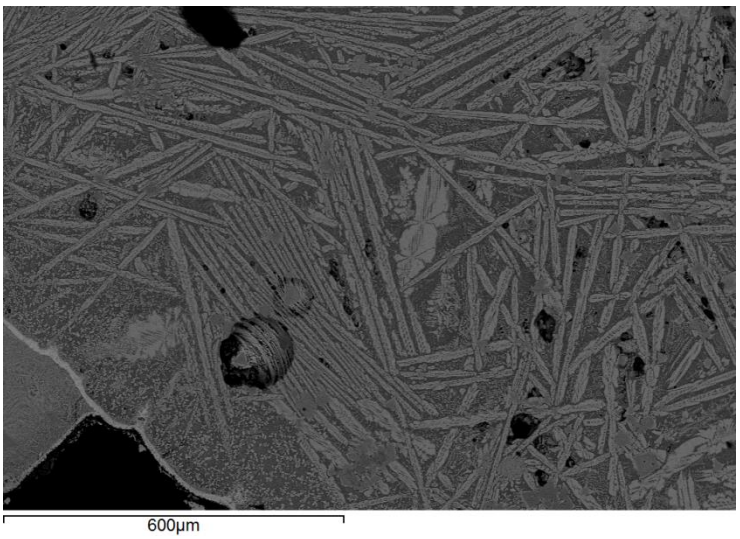

Figure 6.13: SEM-BSE image of a tap line (white) of the smelting slags, sample Malolo1 SE1. Note fayalite (grey), glass matrix (dark grey), and porosity (black)

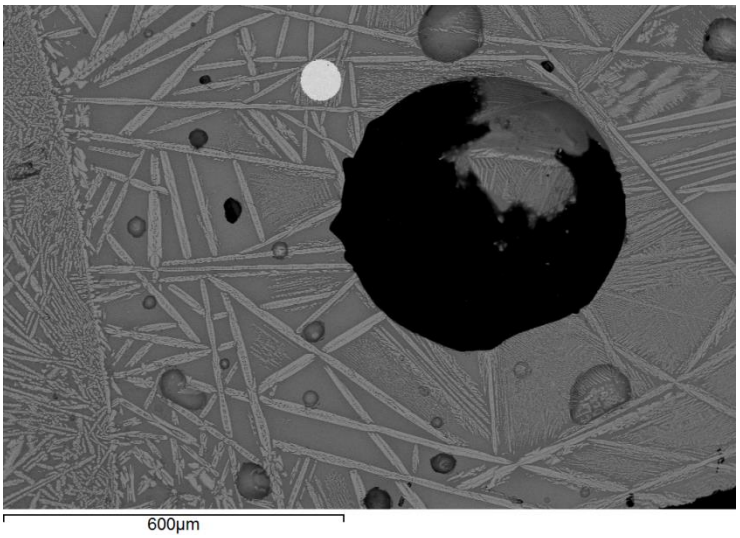

Figure 6.14: SEM-BSE image of a tap line (white) of the refining slags, sample Malolo3B RF5. Note metal droplet (white), fayalite (grey), glass matrix (dark grey), and porosity (black)

6.3.3.5 Wüstite crystals

One refining sample alone showed up some wüstite crystals (Figure 6.15). The microstructures suggest that this sample had started cooling slowly, perhaps in the furnace, before it was raked out to more oxidizing conditions where it cooled relatively quickly. While inside the furnace, it was probably situated far from most reducing conditions or areas that some of its wüstite were not completely reduced by the time bellowing stopped for steel collection. On average, the crystals composed of iron oxide about 97 wt%, alumina, titania and MnO weighed around 1 wt% each. The general absence of wüstite in the other samples is a strong indication of efficient reduction processes or rather better operational skills of the smelters and refiners of this area (see Morton and Wingrove 1969; Chirikure and Rehren 2004; Rehren *et al*. 2007; Mapunda 2010).

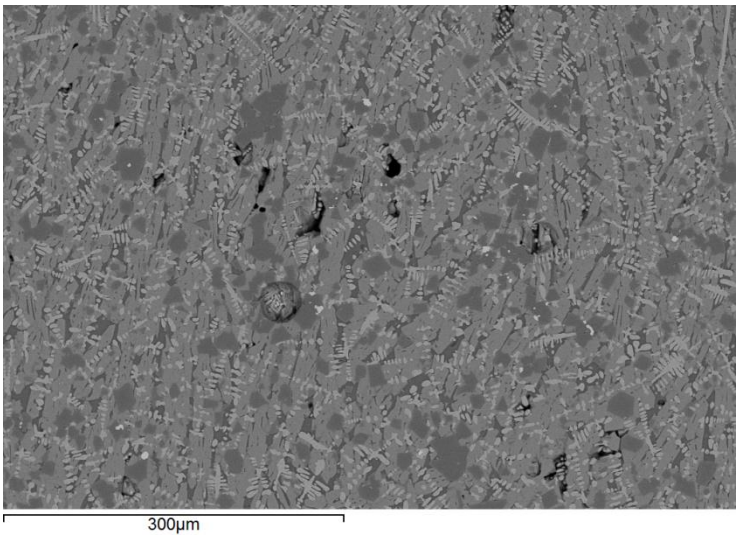

Figure 6.15: SEM-BSE image of the wüstite crystals (dendrites white grey), sample Malolo3B RF4. Note fayalite (grey), hercynite (dark grey), iron (white), glass matrix (dark grey), and porosity (black).

6.3.3.6 Iron droplets

Like in Ufipa, all the refining slags from Unyiha contained iron metal droplets as perfect circles or well-rounded droplets (Figure 6.16). The droplet-nature is a strong

indication of a liquid state, which ‘bloomery’ iron cannot reach unless there is enough carbon (and high temperatures) in the system as it brings its melting temperature down (van der Merwe 1970). In order to test this hypothesis, I conducted electron probe microanalysis (EPMA) of the metal droplets (see Table 6.23). Of interest, on average, carbon measured about 2.3 wt% in the Shihando refining slags, and 2.2 wt% in the Itaka refining slags suggestive of carbon-rich steel production by assuming that the droplets coalesced or were part of the refined (final) product (e.g. Blomgren and Tholander 1986: 156). However, the iron droplets had greatly variable carbon concentrations (see Appendix 6.22) indicative of production of a heterogeneous (solid) final product, mainly high carbon steel with cast iron (see also David *et al*. 1989; Childs 1996). Other alloyants of the steel with cast iron were manganese, silicon, arsenic, cobalt, molybdenum, aluminium, nickel, copper, and phosphate.

Table 6.23: EPMA-WDS chemical composition (in wt%) of the metal droplets from Shihando and Itaka refining sites. Note the results are the average of several spectra and are normalised to 100 wt%, the full results in Appendix 6.22

S/No.	Sample/ Elements	Si	P	Al	Cu	As	Mo	Ni	Co	Mn	C	Fe	AT
1	7RF5	0.07	0.03	0.04	0.03	0.00	0.05	0.01	0.01	0.13	2.47	97.14	99.67
2	7RF6	0.01	0.04	0.03	0.04	0.00	0.15	0.07	0.17	0.15	2.78	96.52	99.74
3	7RF3	0.03	0.01	0.02	0.04	0.21	0.08	0.05	0.06	0.12	1.68	97.69	99.15
4	2RF4	0.31	0.01	0.14	0.01	0.00	0.01	0.01	0.08	0.13	3.24	96.06	99.64
5	2RF6	0.06	0.01	0.03	0.02	0.00	0.02	0.01	0.09	0.06	2.68	97.01	99.22
6	2RF3	0.05	0.07	0.05	0.02	0.27	0.02	0.07	0.09	0.10	0.87	98.36	99.33

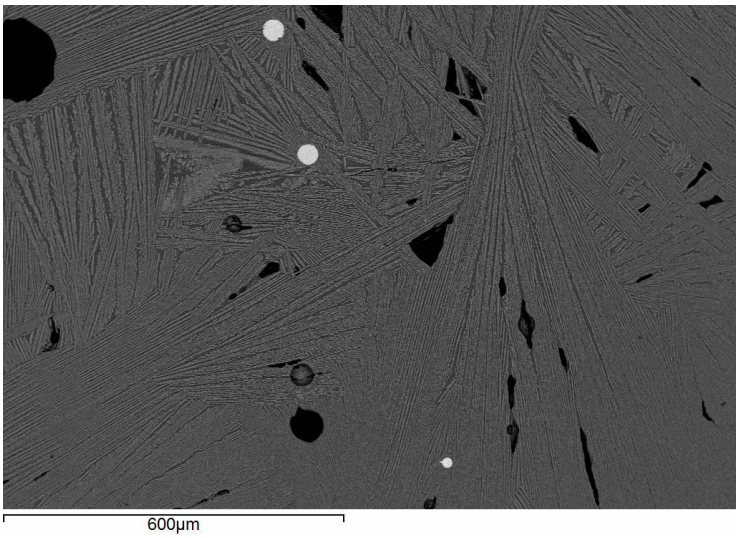

Figure 6.16: SEM-BSE image of the metal droplets (white circles) in the refining slags, sample Shihando7 RF3. Note fayalite (grey), glass matrix (dark grey), and porosity (black).

6.3.3.7 Iron particles

Some of the smelting slags systematically contained angular particles suggesting that they did not reach a liquid state as the metal droplets (Figure 6.17). Based on the shape of the particles, it is possible that they suggest a possible production of 'bloomery' iron as opposed to steel with cast iron (see Tholander and Blomgren 1985: 422). This is supported by a premise that the primary (soft) iron was refined and carburized in the *vintengwe* furnaces in order to produce high carbon steel with cast iron.

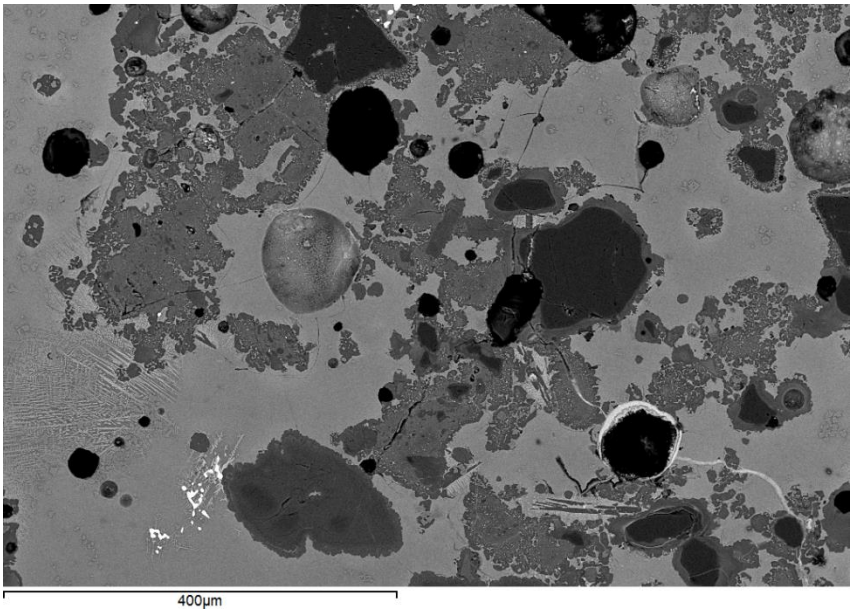

Figure 6.17: SEM-BSE image of the metal particles (white) in the smelting slags, sample Malolo1 SE4. Note fayalite (grey), hercynite (dark grey), glass matrix (dark grey), and porosity (black)

6.3.3.8 Porosity and quartz phases

All the smelting and refining slags are porous, with ill-defined pores and in the shape of perfect circles (Figure 6.18). The quartz are more or less shapeless, but they can be placed into two classes, namely, reacted quartz often with elaborate cracks, and unreacted quartz with less conspicuous or no cracks at all. The former were perhaps part of the metal production process and were exposed to high temperatures, but the latter were sand quartz entrapped while tapping slag.

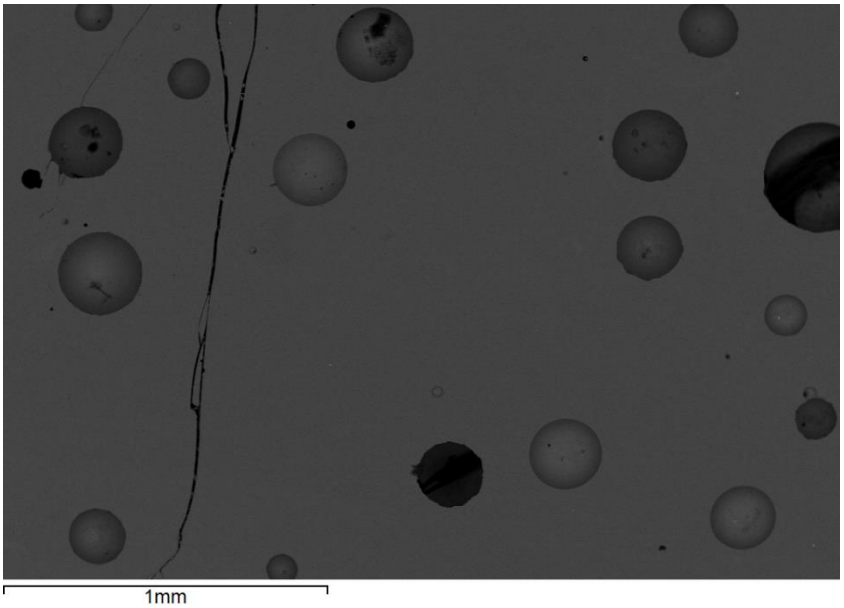

Figure 6.18: SEM-BSE image of round porosity in the slags, sample Malolo3B RF1. Note cracks (black).

6.3.3.9 Other crystals

Of all samples, there were 6 samples with spinels, forming a solid solution of hercynite and magnetite spinels. They are improbably neither pure hercynite nor magnetite, because they have less Al_2O_3 and more FeO for the former and less FeO and more Al_2O_3 for the latter (Table 6.24). It appears that these (hercynite) spinels were oxidized while tapping slag out the furnaces, and ones that formed due to immediate contact with ambient air. As a result of the oxidation process, the Fe^{2+} was being transformed into Fe^{3+}, although the conversion was unsuccessfully accomplished before the slag cooled and solidified (Figure 6.19). It can be noted that the crystals close to the surface (or ambient air) were converted more quickly and in less time than it took to transform those crystals in the interior of the sample (see Figure 6.19).

Table 6.24: SEM-EDS chemical composition (in wt%) of the other crystals in the smelting (SE) and refining (RF) slags from Mbozi. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	K_2O	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
Smelting and refining slags from Malolo											
1	1SE5	0.2	29.5	2.1	0.1	1.0	0.0	0.1	9.4	57.5	100
2	3BRF4	0.3	29.6	1.1	0.0	1.8	0.0	0.0	1.1	66.3	100
Smelting and refining slags from Itaka											
3	1SE1	0.2	8.2	0.6	0.0	1.7	0.1	0.1	2.5	86.7	100
4	1SE2	0.3	19.3	2.0	0.2	3.4	0.6	0.2	2.0	72.0	100
5	1SE4	0.4	21.9	3.5	0.2	4.5	0.5	0.1	4.2	64.6	100
6	1SE5	0.1	11.5	1.1	0.0	1.6	0.2	0.0	1.2	84.2	100

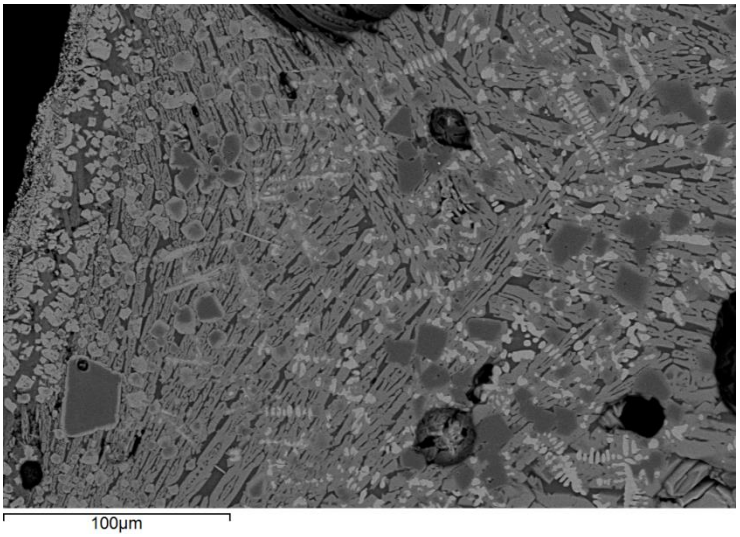

Figure 6.19 SEM-BSE image of the impure spinels (zoned-left edge), sample Malolo3B RF4. Note fayalite (grey), hercynite (dark grey), glass matrix (dark grey), and porosity (black).

6.4 Discussion of the Aims of the Chapter

In Chapter 2 on Previous Archaeological Knowledge in Mbozi, I outlined the aims of the current research in Mbozi including: (1) to examine the nature of refractory quality of the technical ceramics, (2) to investigate air supply mechanism for the *malungu* and *vintengwe* furnaces, (3) to examine handling of the molten slag methods, (4) to examine the reduction efficiency of the furnaces and its associated factors, and (5) to suggest the

nature of the final products from *malungu* and *vintengwe* process. These aims are discussed in the light of both the macroscopic and microscopic data presented above.

First, and based on similarity in refractory quality, the tuyères and furnace walls at Itaka site #1 were possibly from a similar (termite mounds) source, although tuyères were slightly rich in silica (see Figure 6.5). Conversely, tuyères and furnace walls at Itaka site #2 were probably from different sources, because they have different refractory qualities (see Figure 6.6). On the basis of maximum refractory, the tuyères are less refractory than the furnace fragments and pottery. It is noteworthy that the tuyères of both sites were more dimensionally stable than the furnace and pottery samples, because they are rich in silica (see Freestone and Tite 1986).

Second, in addition to the oral and ethnographic information (e.g. Brock and Brock 1965), 10 tuyère ports per *ilungu* smelting furnace, use of multiple tuyères inserted one on top of the other, and the size and height of the *malungu* furnaces strongly support a natural draft operation (see van der Merwe and Avery 1987: 149). What about the *vintengwe* furnaces? Although Mapunda (2010: 157) associates unflared tuyères with natural draft operation, it is important to note that the *vintengwe* furnaces were operated by bellows fitted on unflared tuyères. This exception can be explained, because according to oral evidence, the smelters manufactured the tuyères for the two processes at the same time and used the same method, although the tuyères for the second *vintengwe* process were cut relatively shorter. Apart from that, the refining furnaces were relatively small in size: shorter and smaller than the smelting furnaces with three tuyère ports each housing one tuyère. This information is conventional, because, elsewhere in Tanzania (Barndon 2004; Mapunda 2010), Malawi (van der Merwe and Avery 1987), and Zambia (Phillipson 1968), the *malungu* were operated by a natural draft while *vintengwe* by forced draft mechanism.

Third, and in addition to the evidence of flow nature of the slags, the relatively small, thin, and skeletal microstructures, and the presence of magnetite tap lines in both the smelting and refining slags is indicative of slag tapping technology. The last two sets of microscopic evidence for slag tapping are critically a good verification, because flow slags can come from a non-slag tapping technology as well (see Chirikure 2006: 148, Haaland and Msuya 2000: 82). The presence of tuyère-moulds slags at the smelting sites suggests that slag tapping was done through the tuyères, and the absence of such tuyère-moulds slags at the refining sites denies such a possibility (for details on slag tapping through tuyères, see Chapter 2, subsection 2.3.1; Mapunda 2010: 154). According to Brock and Brock (1965: 98), slag tapping or rather slag draining with the refining furnaces was done through a large tunnel dug below the tuyères level and down the slope. Similar practises have been observed in Ufipa (Greig 1937: 79; Wise 1958: 110).

Fourth, the lack of primary high free iron oxides in the slags suggests the smelting and refining processes were technically efficient. In particular, the virtual absence of wüstite crystals in the slags strongly suggests that more reducing conditions were reached (Morton and Wingrove 1969; Tylecote *et al*. 1971; Killick 1990; Ige and Rehren 2003). The reduction efficiency of the primary *malungu* stage, among other factors, was due to the use of iron ore rich in manganese. The presence of enough manganese in the process replaced some iron to go into the slag, because ideally 2 mol of MnO would combine with 1 mol of silica to form slag rich in tephroite crystals, although in our case, 2 mol of each MnO and FeO combined with silica to form slag rich in knebelite crystals (see Iles and Martinón-Torres 2009: 2323; Charlton 2006; Charlton *et al* 2010: 365). For both processes, the other factors for the efficiency would have included (1) fuel to ore (or iron) ratio (e.g. Killick 1991; Rehren *et al*. 2007), and (2) efficient and constant air

supply (e.g. Schmidt and Avery 1978; Childs 1996), all of which reflects better skills of the smelters (and refiners). Figure 6.8 showed that most of the smelting and refining slags cluster more or less around the Optimum zone 1 (Rehren *et al*. 2007: 213), with slag melting temperatures *circa* 1100-1300 ^{o}C.

Lastly, I predicted that the second *vintengwe* process must have been technologically and functionally different from the first *malungu* stage. To test this hypothesis, I examined whether or not the smelters and refiners desired different final products by the two processes. According to Tholander and Blomgren (1985: 422) and Tholander (1989: 38), the presence of the wüstite and angular iron particles in the smelting slags on one hand, and the absence of wüstite and presence of iron droplets in the refining slags on the other, can be a strong indication of producing (soft) or 'bloom' in the former, and high carbon steel in the latter. The chemical data of the iron droplets (see Appendix 6.22) suggest that it was heterogeneous high carbon steel with cast iron that were systematically produced in the *vintengwe*, and *not* (liquid) cast iron (e.g. Tholander 1987). In Ufipa the first impure soft iron was called *untale* or *mtale*, and the second hard steel with cast iron was called *ululu* or *mlulu* (see Chapters 5 & 10). The production of heterogeneous steel with cast iron relates to sporadic earlier studies elsewhere on the continent (e.g. Childs 1996; David *et al*. 1989). On the basis of conventional classification, the *vintengwe* process does not qualify to be blast furnace process, but one that sits between the 'bloomery' and Eurasia blast furnace processes. The use of the second stage to produce steel with cast iron is interesting, because so far, we had thought steel (and cast iron) was produced in sub Saharan Africa through the first ore smelting stage alone (van der Merwe and Avery 1982, David *et al*. 1989, Childs 1996). Now we have a laboratory (slag) method to look for this second stage tradition elsewhere in Africa.

6.5 Summary

The main purpose of this chapter was to verify the presence of the *vintengwe* process by differentiating it from the remains of the *malungu* process. Besides the ethnographic information (e.g. Brock and Brock 1965; Ngonadi 2010), the presence of the refining process is verified and supported by both the macroscopic and microscopic evidence. Macroscopically, the refining sites are different from the smelting sites in terms of size, the refining sites are smaller in size compared to the smelting sites, but also location as the refining sites are not confined to the western side of termite mounds as a necessary requirement for the smelting sites, it appears that the slope mattered technically for the location of refining sites. They are also different in terms of heap composition and slag types where the refining sites relatively compose of virtually flow slags alone, fewer tuyères and furnace walls, but the smelting sites are exclusively characterised by ore remnants, tuyère-mould slags, and double or triplets tuyères in addition to blocky slags and lots of furnace walls.

Chemically, there is a systematic observation of more FeO in the refining slags than in the smelting slags (see Figure 6.8), and microscopically, there is an exclusive presence of metal droplets in the refining slags, while metal particles are found in the smelting slags. The refining product, based on the chemical data of the droplets, was meant to be high carbon steel with some cast iron pockets, and this information support, in a way, earlier observations elsewhere on the continent (e.g. David *et al*. 1989: 197; Childs 1996).

On the basis of the new information, metal production in this area followed a three-stage process, just like their neighbouring Fipa. The first stage was ore (rich in Mn^{2+}) smelting in tall furnaces, the second was meant to melt and refine the product of the first stage, and the third was the work of forging tools.

Both the first and second were technically efficient processes, based on the lack of high free iron oxides, and for the sake of successful ore smelting and metal refining processes, the ironworkers probably chose refractory termite mound clays for the construction of especially furnaces and tuyères.

7. Iron and High Carbon Steel Production in Mbinga

7.1 Preamble

This chapter focuses on the iron smelting process in Mbinga district (Figure 7.1) located in Ruvuma region. The area is generally referred to as Umatengo, because the majority of the indigenous people are Matengo (LOT 2009: 98). This chapter presents and interprets new macroscopic and microscopic data, including a discussion of the aims of this chapter in light of the new data. The chapter concludes with a summary, providing a synthesis of the spatial and temporal differences between the early (Ntuha) and later (Kigonsera) ironworking technologies in Mbinga.

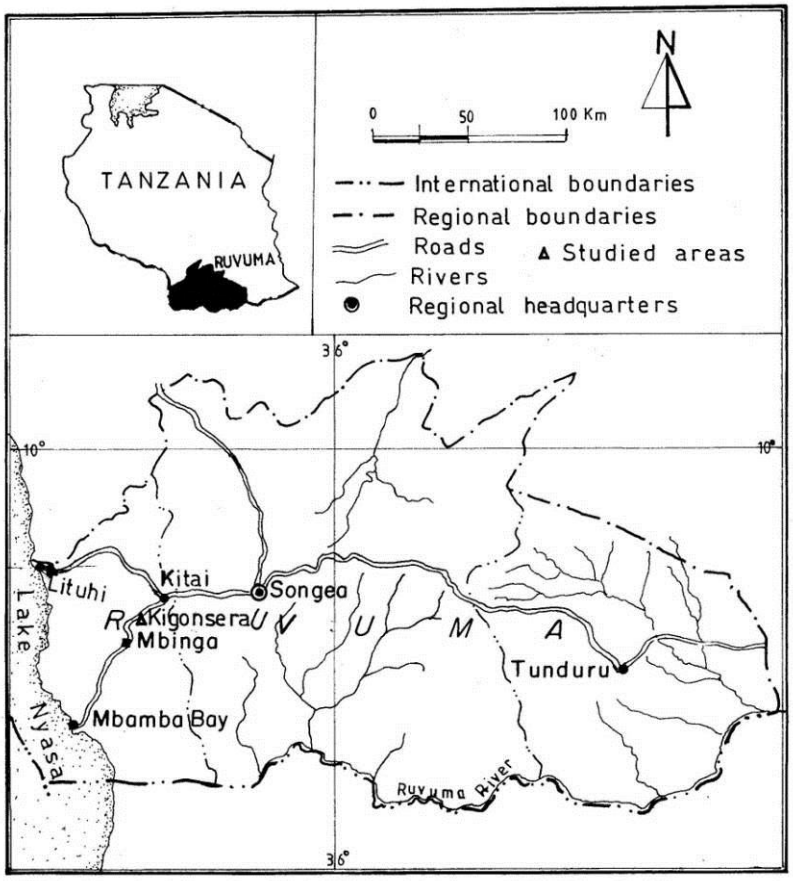

Figure 7.1: Map of Ruvuma showing Mbinga and locations of Lituhi and Kigonsera wards

7.2 Presentation and Interpretation of Macroscopic Data

7.2.1 Sites: Location, Size, Preservation, and Context of the Material

7.2.1.1 Location

The current archaeological research in Mbinga was conducted in two administrative wards, Lituhi and Kigonsera. In Lituhi ward, I re-excavated Ntuha sub-village site (referred to as IiJc-4 by Mapunda 1991) (Figure 7.2). It is located at latitude S (10^{o} 34' 30'') and longitude E (34^{o} 40' 05''), about 756 m above mean sea level, and it dates to the mid-first millennium AD (Mapunda and Burg 1991: 35). As well as the excavation, a few specific surface collections were made.

Fieldwork research in Kigonsera ward was conducted in five villages: Mkulusi, Kihuluku, Matalawe, Halale, and Minazi (see Figure 7.2). Being the first archaeological field survey in these villages, I discovered and recorded a total number of 31 sites, ranging from smelting and smithing to pottery sites (Appendix 7.1 through 7.4). Out of these sites, 14 were discovered around Mkulusi village, four in the vicinity of Kihuluku, eight around Matalawe, one at Halale, and four at Minazi village (see Appendix 7.1 through 7.4). Based on GPS location data, all the sites in Kigonsera ward are located between latitudes S (10^{o} 43' and 10^{o} 54') and between longitudes E (35^{o} 4' and 35^{o} 7'). They are situated between 960 and 1150 m above mean sea level. In contrast to the smelting sites of Unyiha (see previous chapter), there is no evidence of termite mounds near the smelting sites but it would seem that the iron smelters of eastern Umatengo located the smelting close to sources of water mainly rivers and natural wells, within a distance of 76 m on average (see Appendix 7.1 through 7.4). As well as the need to be close to water for the construction of the furnaces and manufacturing of tuyères and pottery, or for personal uses (e.g. Mapunda 2010), it can be argued that they also wanted

to be close to the allegedly black (magnetite) sand ores from the river valleys (Kapinga 1990).

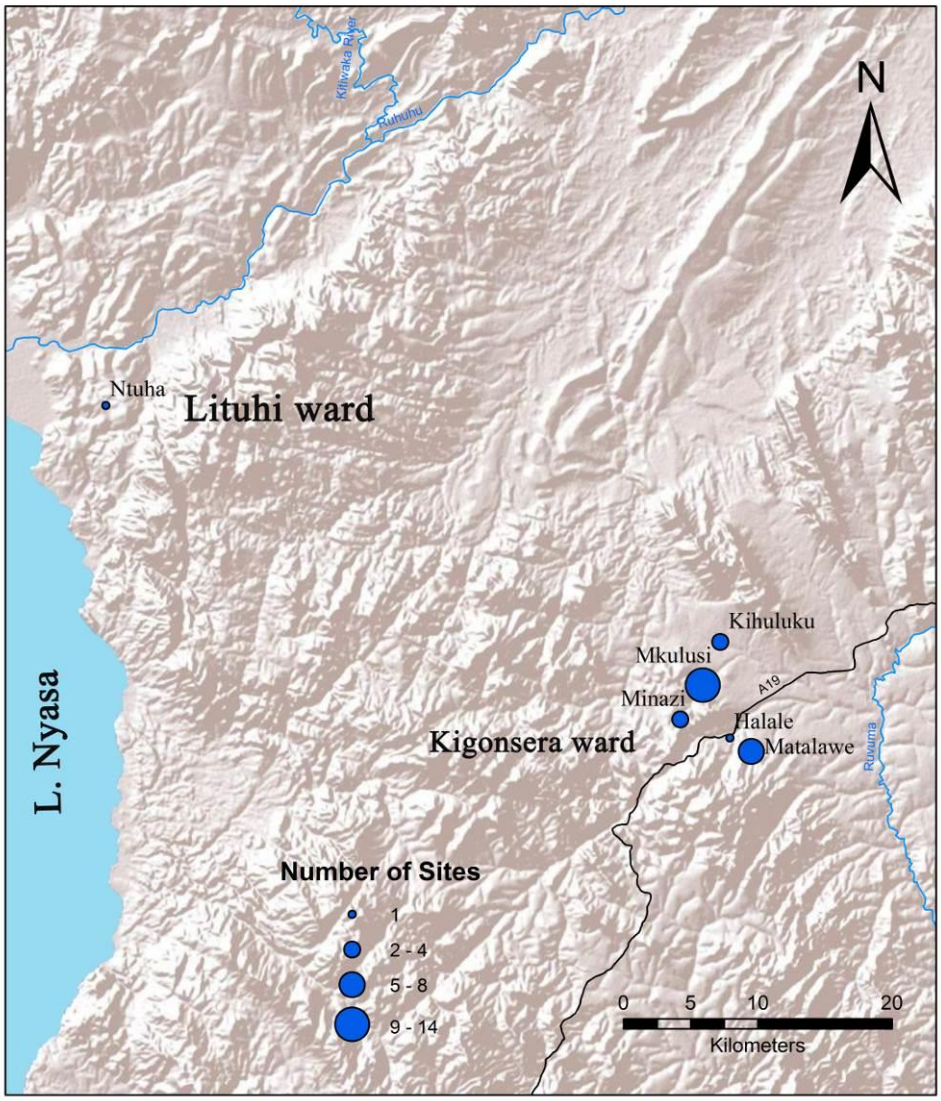

Figure 7.2: Map of Kigonsera and Lituhi wards showing the location of the studied villages and the number of the sites per village

7.2.1.2 Area size

Ntuha (IiJc-4) in Lituhi ward is about 700 m^2 in area. The smelting sites of Kigonsera, on average, have sizes ranging between 120 and 210 m^2, but the recent smithing site had an area size of about 48 m^2, and the pottery sites measured about 80 m^2 on average.

Almost all of the smelting sites are well preserved (see below), and their relatively larger sizes compared to the smithing and pottery sites is apparently due to the bulkier nature of the raw materials and composition of the resultant debris. Similarly, the smelting sites of Umatengo are relatively smaller than the smelting sites of Unyiha as described in Chapter 6, which had an average of about 589 m^2 area size, because the former employed relatively small smelting furnaces but the latter involved relatively very large and tall smelting furnaces.

7.2.1.3 Preservation

Given its relatively old age (see Appendix 4.7); it might be assumed that much of the Ntuha site record is still buried. Although the materials are found in undisturbed stratigraphic contexts, some of the material especially that in the upper cultural levels has been exposed and consequently transported by water erosion downhill. On the other hand, almost all the smelting sites from Kigonsera are relatively well preserved. With the exception of Mkulusi site 1, none of the sites are situated in people's farms and thus they are well preserved. Interestingly, Mkulusi site #1 is located in a farm, but it was encircled and protected by the farmers, although this was probably to avoid large heaps of slags that make the ground difficult to cultivate rather than a move to protect the site itself. All the Matalawe sites are well preserved, but some of the Kihuluku and Minazi smelting sites are situated in people's farms and have been treated in the same way as Mkulusi site #1. Since these sites have value for heritage purposes as well as for archaeological research, two public talks were conducted respectively with village leaders in the first instance and later with the general community in order to raise awareness among the people on these cultural heritage resources located in farms.

7.2.1.4 Context of the material

I excavated Unit 3 of Ntuha (IiJc-4) and retrieved samples of ceramic, slag and stone for archaeometric analysis (Table 7.1). In addition, surface collections were made including two fragments of furnace walls, daub pieces often with wood impressions, five tuyère, and four slag samples.

Table 7.1: Materials from Unit 3 at Ntuha (IiJc-4) smelting site

S/No.	Level	Furnace walls	Daub (impressed)	Slags	Tuyères	Potsherds	Lithics	Charocal
1	A (0-10)	20	2	69	9	6	15	-
2	B (10-20)	54	1	481	39	11	11	2
3	C (20-30)	16	1	240	17	-	3	9
4	D (30-40)	5	-	29	-	-	5	-
5	E (40-50)	1	-	5	31	-	6	-
6	F (50-60)	-	-	7	-	-	-	3
7	G (60-70)	sterile level						
8	**Sum**	**96**	**4**	**831**	**96**	**17**	**40**	**14**

The materials collected from the eastern Umatengo (Kigonsera) sites were surface collections and excavated materials from Mkulusi site #1 and Mkulusi site #7 furnaces. These were excavated owing to the presence of intact furnace bases and in search for droplet slags as indicators of slag-pit furnaces. Mapunda (1991: 7, 69) has argued that the Matengo ironworking was a non-slag tapping technology. In addition, it was in search of tuyère-mould slags in case the smelters tapped slags via tuyères as the Nyiha and Fipa smelters did as well as in search of the allegedly *indipa* and *imbaba* ritualistic pots as claimed by Kapinga (1990: 19). The materials from the excavations are respectively presented in Table 7.2 and Table 7.3. The macroscopic attributes of the materials are discussed below.

Table 7.2: Quantity of the excavated materials from Mkulusi smelting site 1. Note that IF stands for inside the furnace Unit 1, and OF stands for outside the furnace Unit 2

S/No.	Level (cm)	Furnace walls	Slags		Tuyère		Pottery		Charcoal	Remarks
			Flow	Droplets	Flared	Unflared	Decorated	Undecorated		
1	A (0-10)	7	20	-	-	-	-	6	-	IF1
2	B (10-20)	5	-	-	-	-	-	5	6	IF1
3	C (2-30)	-	4	-	-	-	-	-	5	IF1
4	D (30-40)	sterile level								IF1
5	A (0-10)	2	7	-	-	-	-	6	-	OF2
6	B (10-20)	3	5	3	1	5	-	-	-	OF2
7	C (2-30)	3	-	1	-	-	-	4	3	OF2
8	D (30-40)	5	-	2	-	-	2	-	2	OF2
9	E (40-50)	2	3	1	-	-	-	-	4	OF2
10	F (50-60)	sterile level								OF2
11	**Sum**	**27**	**39**	**7**	**1**	**5**	**2**	**21**	**20**	

Table 7.3: Quantity of the excavated materials from Mkulusi smelting site 7. Note that IF stands for inside the furnace Unit 1, and OF stands for outside the furnace Unit 2

S/No.	Level (cm)	Furnace walls	Slags		Tuyère		Pottery		Charcoal	Remarks
			Flow	Droplets	Flared	Unflared	Decorated	Undecorated		
1	A (0-10)	18	6	-	-	2	-	-	6	IF1
2	B (10-20)	-	20	-	-	-	-	-	-	IF1
3	C (2-30)	1	17	-	-	-	-	-	-	IF1
4	D (30-40)	-	8	-	-	2	-	-	-	IF1
5	E (40-50)	sterile level								IF1
6	A (0-10)	-	104	-	-	3	-	1	-	OF2
7	B (10-20)	-	57	1	-	1	-	2	-	OF2
8	C (20-30)	-	33	-	1	1	-	-	-	OF2
9	D (30-40)	-	-	-	-	-	-	-	-	OF2
10	E (40-50)	sterile level								OF2
11	**Sum**	**19**	**245**	**1**	**1**	**9**	**0**	**3**	**6**	

7.2.2 Furnace Attributes

7.2.2.1 Furnaces of Lituhi ward

With the exception of the furnace walls and the impressed daub-like, no complete standing smelting furnaces have been discovered at the Ntuha site, making it difficult on the basis of the recovered materials to suggest the exact shape of the smelting furnaces of this area (see also Mapunda 2001: 108). The furnace walls and daub-like ceramics from this site are quite different, in that the former is relatively less crumbly and more compact with no impressions, while the latter is quite crumbly with wood impressions (Figure 7.3). According to Mapunda (1991: 52), the daub-like flat surfaces faced upward, the side with the impressions faced downward, and the impressions were uniform in diameter and spaced evenly. The difference in crumbling nature was possibly due to differences in their exposure to temperature, while the absence or presence of the impressions suggests that they possibly belonged to two different structures. I consider two possibilities: (1) there could have been a temporary house structure next to the smelting furnaces, or (2) a charging platform was built on top of the smelting furnace. With the first option, there are two or three problems, namely, there is no archaeological evidence of a house structure whatsoever nearby the site, and secondly, it is known from ethno-history that iron smelting activities in Umatengo were secluded from residential areas (e.g. Kapinga 1990; Mapunda 2001), although elsewhere smelting rarely was conducted within settlements (see Haaland and Msuya 2000; Haaland 2005; Chirikure 2005). Lastly, fallen house daub remains would have not well-survived since the 1st millennium AD unless fired. The second option appears the best explanation, because there is a comparative material example of a technological practice of smelting furnaces with charging platforms is well-documented in the areas of Togo hills and southern parts of Ghana by the Mawu people (Pole 2010: 53, fig. 3).

Unfortunately, there are no parallel materials from geographically closer areas of a charging platform. If a charging platform was a necessary requirement for the smelting furnaces, then it is safe to argue that the Ntuha smelting furnaces were relatively taller than the recent furnaces, well above 1.5 m. This inferred height of over 1.5 m coupled with the suggestion of nine or ten tuyères per furnace (Mapunda 1991: 69) seem to support the suggestion that natural draft mechanisms were used here. Because they encountered two large stones at Ntuha, which were supposedly used to protect the bellowers from the furnace heat, Mapunda (1991: 69) has argued for a forced draft mechanism. Nevertheless, the stones could have been also used for ritual purposes as guarding stones, for instance, or for other technical reasons such as sealing the tuyère ports during furnace construction (see Pole 2010: 55). Therefore, unless we have flared ends of the tuyères from Ntuha sites, it appears very much that the smelting furnaces at this site were operated by a natural draft.

Figure 7.3: Possible furnace platform daubs of Ntuha (IiJc-4) site with wood impressions

7.2.2.2 Furnaces of Kigonsera ward

Unlike at Unyiha, the fieldwork in Kigonsera did not discover still standing smelting furnaces. The absence of such furnace remains, it can be argued, could have been due to the fact that while the smelting furnaces of Unyiha were built to serve several smelting seasons or years, the relatively short and small size of the Matengo furnaces (Kapinga 1990: 17) were designed to serve one smelting season, only after which they were dismantled (see also Sutton 1985). Nevertheless, it has been possible to discover four possible furnace bases, one in Halale, one in Minazi and two in Mkulusi village. Given the fragmentary nature of these iron smelting furnaces (Figure 7.4), and for the purposes of comparison, our measurements were restricted to the bases alone (Table 7.4). On average, the smelting furnaces had external base diameters (EBD) of 85 cm, with internal diameters of about 67 cm, and with base wall thicknesses (BWT) of about 9 cm. The standard deviation (SD) figures show that there is more consistency with the wall thickness dimensions as well as the external diameter than the internal diameter. The iron smelting furnaces of western Umatengo (Kapinga 1990) with base diameter of 1 m were relatively larger than the smelting furnaces of the eastern Umatengo. Nevertheless, the eastern Umatengo *matendi* smelting furnaces were relatively larger than the *vintengwe* refining furnaces and smaller than the *malungu* smelting furnaces of Ufipa and Unyiha (Mapunda 2010; Ngonadi 2010).

As noted earlier, Mkulusi smelting sites 1 and 7 were excavated (for details of the excavation see Chapter 4, and for a context of the materials see this chapter). The excavation of the sites suggests that the *matendi* smelting furnaces had such shallow pits (about 15 to 20 cm deep) that it is unlikely they were used as slag-pits. If this is true, then it is possible to propose that the liquid slag was tapped out of the furnaces during the metal production process. This interpretation is strengthened by the small size of the

slag crystals (for details, see microscopic data section), and it could challenge Mapunda's (1991: 7, 69) proposal for non-slag tapping furnaces in Umatengo. In addition, the excavations retrieved pottery buried underneath the furnace. This attests the oral and ethnographic information (e.g. Kapinga 1990: 19) about *indipa* and *imbaba* medicinal pots that were necessary for successful smelts (for similar observation elsewhere in Ludewa district, see Schmidt 2006: 158).

Table 7.4: Dimensions of the iron smelting furnaces bases from Kigonsera sites. Note that EBD stands for external base diameter, IBD for internal base diameter, and BWT for base wall thickness

S/No.	Site Name	EBD (cm)	IBD (cm)	BWT (cm)
1	Halale SE1	85	65	10
2	Minazi SE1	88	72	8
3	Mkulusi SE1	84	66	9
4	Mkulusi SE7	83	63	10
5	**Average**	**85**	**67**	**9**
6	**SD**	**2**	**4**	**1**

Figure 7.4: Photograph of a furnace base of Mkulusi smelting site #7. The double (black) arrow line points to tuyère port positions

7.2.3 Tuyère Ports and Tuyères

7.2.3.1 Tuyère ports and tuyères of Lituhi ward

7.2.3.1.1 Tuyère ports per furnace and tuyères per port

No furnace or its base has been recovered from the Ntuha site, which makes it impossible even to guess the number of tuyère ports per furnace. It is unclear from Mapunda (1991) whether the nine or ten tuyères per furnace represent two or more ports, but if we think the air supply into the furnaces was through a natural draft as pointed out earlier, it can be argued that the number should represent more than two tuyère ports.

7.2.3.1.2 Tuyère attributes

None of the recovered tuyères from this site had flared proximal ends indicative of a forced draft operation, but they are relatively large (Figure 7.5) with external diameters averaging 7 cm, internal diameters averaging 4 cm, and with wall thicknesses averaging 2 cm (Table 7.5). These average dimensions make them larger than the tuyères of the Kigonsera sites (see below). With a SD of 0.5 cm, it can be suggested that the internal diameters were quite similar, which could have been due to the use of a similar stick for their production. In addition, a SD of 1 cm suggests that efforts were made by the smelters to make the external diameters consistent in size as well. Most of the distal ends of the tuyères are slag-coated or show signs of slag flow-back, and occasionally they were exposed to high smelting temperatures for they are sporadically bloated. There is no evidence that the tuyères at this site were used to tap slag. If slag tapping was practised, then it must have been through a tunnel or hole at the base of the furnace. Nevertheless, the slag mineralogical evidence below does not support slag-tapping practice at this site either (for details, see mineralogical data section).

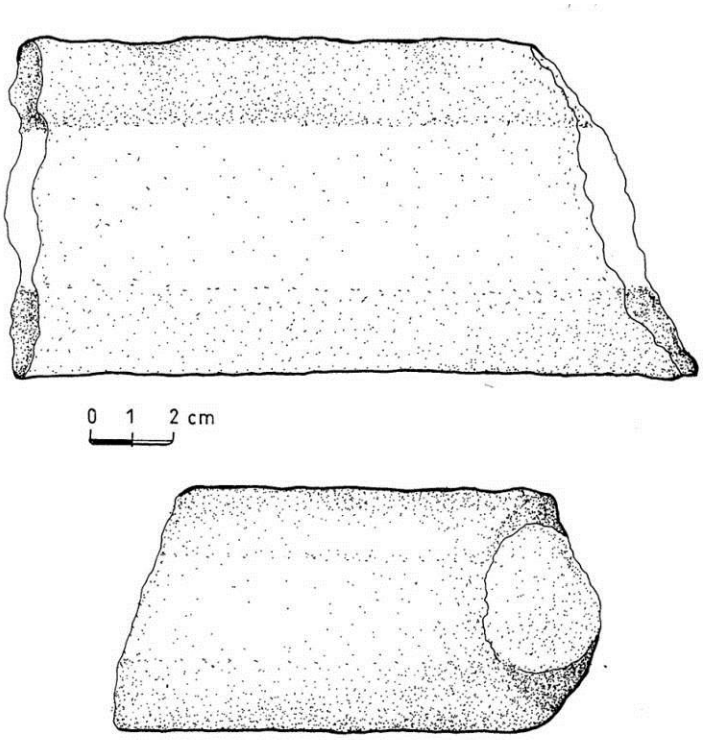

Figure 7.5: The tuyères of the Ntuha (IiJc-4) site

Table 7.5: Macroscopic attributes of the tuyères from Ntuha (IiJc-4) smelting site. Note that ED stands for external diameter, ID for internal diameter, and SD stands for standard deviation

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Segment	Remarks
1	Ntuha	8.0	4.0	2.0	Body/distal	slags run back
2	Ntuha	6.0	3.0	1.5	distal	slags coated
3	Ntuha	6.2	3.9	1.2	body	
4	Ntuha	7.0	3.4	1.8	distal	slags coated
	Average	**7**	**4**	**2**		
	SD	**1**	**0**	**0**		

7.2.3.2 Tuyère ports and tuyères of Kigonsera ward

7.2.3.2.1 Number of tuyère ports per furnace

In eastern Umatengo, it has been difficult to tell with precision the exact number of tuyère ports per smelting furnace, but based on the archaeological evidence from

Mkulusi site #7, of a relatively less fragmentary furnace base, it is likely that the smelting furnaces at this site had two tuyère ports facing each other (see the arrows on Figure 7.4 above). This is not a highly surprising observation, because elsewhere in western Umatengo, Kapinga (1990) was given a similar description. Although it was not possible to determine the height of the ports due to the fragmentary nature of the furnace base, on average the two tuyère ports from Mkulusi measured 23 cm wide. This is interesting, because they were wider than the ordinary tuyère ports of the tall and larger *malungu* smelting furnaces of Unyiha for example, which measured between 15 and 20 cm wide (see the previous chapter, furnace attributes section). Unlike the tuyère ports of Unyiha with tuyères inserted into the ports horizontally one on top of the other, the tuyère ports in this area were wider (and possibly lower) in order to accommodate multiple (three or four) tuyères inserted into each of the ports horizontally, one beside the other (see Kapinga 1990: 16). The fact that I recovered multiple tuyères cemented together (Figure 7.6) strengthens and supports Kapinga's observations elsewhere in western Umatengo (see Appendix 7.5, source: Kapinga 1990: 16).

7.2.3.2.2 Number of tuyères per port

It has been difficult to tell the number of tuyères per port with precision, but given the average external diameters of the tuyères of *circa* 6 cm (Table 7.6) three (or four with a peep hole *kilokombi* tuyère) tuyères per port can be suggested. This number of tuyères is very close to Kapinga's observations (1990) of four or five tuyères per port, and the encounter of flared tuyères (Figure 7.7) from Mkulusi smelting sites 1 and 7 perfectly accords Kapinga's (1990) suggestion of a forced draft mechanism for these furnaces. The use of multiple tuyères in a forced draft smelting furnace is interesting, because the popular and conventional knowledge elsewhere on the continent is that the use of multiple tuyères has been associated with natural draft smelting furnaces (e.g. Mapunda

2010: 126; Chirikure 2006: 146). This general understanding should therefore be used with great care, and there is need to consider other factors such as the size and height of the respective furnaces (see van der Merwe and Avery 1987: 149) when exploring possibilities of draught mechanisms of ancient furnaces.

Figure 7.6: Multiple tuyères from Mkulusi smelting site #1

Table 7.6: The macroscopic attributes of the tuyères from Kigonsera ward smelting sites. Note that ED stands for external diameter, ID for internal diameter, and SD stands for standard deviation

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Segment	Remarks/ Inclusions
1	Mkulusi1	5.5	3.1	1.2	body	Sand quartz
2	Mkulusi1	6.4	3.8	1.3	distal	Sand quartz
3	Mkulusi1	5.7	2.9	1.4	body	Sand quartz
4	Mkulusi7	5.7	2.9	1.4	distal	Sand quartz
5	Mkulusi7	5.8	3.4	1.2	distal	Sand quartz
6	Mkulusi7	5.4	3.2	1.1	body	Sand quartz
7	Mkulusi8	5.4	3.0	1.2	distal	Sand quartz
8	Mkulusi8	6.3	3.8	1.3	body	Sand quartz
9	Matalawe1	6.2	4.0	1.1	distal	
10	Matalawe5	5.6	3.0	1.3	body	
11	Matalawe6	6.0	3.2	1.4	distal	
12	Matalawe7	6.3	4.2	1.1	distal	
13	Halale1	6.3	3.9	1.2	distal	slag-coated
14	Minazi1	6.0	3.2	1.4	body	
15	Minazi2	5.5	3.3	1.1	body	
16	Kihuluku1	6.5	3.5	1.5	body	
17	Kihuluku2	6.3	3.3	1.5	body	
18	Kihuluku4	6.4	3.6	1.4	body	
19	**Average**	**6.0**	**3.4**	**1.3**		
20	**SD**	**0.4**	**0.4**	**0.1**		

Figure 7.7: The flared proximal ends of tuyères from Mkulusi sites 1 (top and right), and 7 (left)

7.2.3.2.3 Tuyère attributes

On average, the tuyères of Kigonsera measure about 6 cm external diameter, about 3 cm internal diameter, and their walls are about 1 cm thick (see Table 7.6). Compared to the tuyères of Unyiha, which have an external diameter of 5.7 cm on average (see the previous chapter, tuyère attributes section), the tuyères of this area are slightly larger. However, with regards to the internal diameter, which is important in terms of the amount of air supplied to the furnace (e.g. Klapwijk 1986a), the former and the latter are notably similar, each with 3 cm internal diameters on average. Nevertheless, based on the standard variation figure of 0.4 cm for the external as well as internal diameters of the tuyères of this area, it can be argued that the Kigonsera iron smelters were using a more consistent and standardized methodology of manufacturing the tuyères for the smelting process than the Nyiha iron smelters. The SD figures for the external and

internal diameters of the tuyères of Unyiha were 0.9 cm and 0.3 cm respectively (see previous chapter).

7.2.4 Slag Attributes

7.2.4.1 Smelting slag attributes from Lituhi ward

According to Table 7.7, and with the exception of the cake slag (CK), the slags from Lituhi are similar to the flow slags of Kigonsera (see below) in terms of weight, length, width and thickness. However, most of the former tend to have rough surfaces, with only a minority exhibiting smooth flow textures. The general roughness of the slags as well as the presence of large cake slags suggest that they were perhaps not tapped out of the furnaces. They are reddish and orangey grey and have relatively more corroded surfaces than the Kigonsera slags. The reddish colour and corrosion are possibly due to the relatively high ferro-magnetic property of most of the Ntuha slags tested using pencil magnets.

Table 7.7: Some of the macroscopic attributes of the smelting slags from Ntuha (IiJc-4) site

S/No.	Context	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Surface (CK)	210	10	8	4
2	Level 1	90	4	3	2
3	Level 2	60	7.7	4.7	1.5
4	Level 3	30	9	4.5	1.3
5	Level 4	88	6.4	4	2.7
6	Level 5	102	7.2	5.3	1.7
7	**Average**	**97**	**7**	**5**	**2**
8	**SD**	**61**	**2**	**2**	**1**

7.2.4.2 Smelting slag attributes from Kigonsera ward

Tables 7.8 through 7.12 present measurable slag attributes from some of the Kigonsera sites. Based on these attributes, the slags from this area are very similar to each other in terms of weight, length, width and thickness. This similarity can be used to suggest that a similar method was used to handle them particularly while hot.

Table 7.8: Some of the macroscopic attributes of the smelting slags from Mkulusi site #1

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Mkulusi1	99	6.1	4.1	3.3
2	Mkulusi1	137	8.3	6.0	2.2
3	Mkulusi1	96	9.2	5.3	2.3
4	Mkulusi1	123	6.4	6.1	2.0
5	Mkulusi1	63	4.4	3.9	3.1
6	Mkulusi1	178	14.1	6.4	3.3
7	Mkulusi1	82	8.7	3.7	1.6
8	Mkulusi1	131	7.8	7.0	2.1
9	Mkulusi1	118	5.7	4.1	3.0
10	Mkulusi1	59	5.6	3.2	2.1
11	**Average**	**109**	**8**	**5**	**3**
12	**SD**	**36**	**3**	**1**	**1**

Table 7.9: Some of the macroscopic attributes of the smelting slags from Mkulusi site #7

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Mkulusi7	164	8.4	6.8	3.6
2	Mkulusi7	174	5.6	4.4	2.8
3	Mkulusi7	86	5.5	3.9	2.7
4	Mkulusi7	80	5.5	3.8	2.8
5	Mkulusi7	83	7.8	4.5	3.1
6	Mkulusi7	118	6.8	4.4	2.6
7	Mkulusi7	76	8.2	3.7	1.4
8	Mkulusi7	92	6.3	5.6	2.9
9	Mkulusi7	96	11.8	3.0	1.1
10	Mkulusi7	162	8.0	6.3	2.0
11	**Average**	**113**	**7**	**5**	**3**
12	**SD**	**39**	**2**	**1**	**1**

Table 7.10: Some of the macroscopic attributes of the smelting slags from Kihuluku site #1

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Kihuluku1	221	9.1	6	3.9
2	Kihuluku1	54	4.1	4	2.5
3	Kihuluku1	119	4.4	4.7	4.2
4	Kihuluku1	68	5.2	4.6	3
5	Kihuluku1	56	5.5	3.7	2.7
6	Kihuluku1	57	4.8	4.1	2
7	Kihuluku1	78	4.5	4.3	2.9
8	Kihuluku1	135	7.2	4.5	2.7
9	Kihuluku1	306	8.4	8.1	3.5
10	Kihuluku1	274	6.1	5.8	3.9
11	**Average**	**137**	**6**	**5**	**3**
12	**SD**	**96**	**2**	**1**	**1**

Table 7.11: Some of the macroscopic attributes of the smelting slags from Matalawe site #1

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Matalawe1	66	3.5	2.9	2.6
2	Matalawe1	99	5.5	4	2.9
3	Matalawe1	95	7.7	4.7	1.5
4	Matalawe1	96	9.1	4.5	1.3
5	Matalawe1	88	6.4	4.2	2.7
6	Matalawe1	100	7.2	5.3	1.7
7	Matalawe1	62	5.8	3.9	2.1
8	Matalawe1	64	5.4	4.8	1.7
9	Matalawe1	93	8.4	4.7	2.1
10	Matalawe1	145	9.8	6.9	2.4
11	**Average**	**91**	**7**	**5**	**2**
12	**SD**	**24**	**2**	**1**	**1**

Table 7.12: Some of the macroscopic attributes of the smelting slags from Minazi site #1

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Minazi1	79	4.5	3.8	1.8
2	Minazi1	84	8.1	4.6	2.2
3	Minazi1	104	5.2	5	1.8
4	Minazi1	167	6.3	3.1	2.5
5	Minazi1	198	9.8	4.9	2.4
6	Minazi1	83	5.3	3.4	3.8
7	Minazi1	62	4.9	3.7	2.4
8	Minazi1	72	8.3	4.3	2.9
9	Minazi1	93	2.3	1.6	1.5
10	Minazi1	94	2.3	1.6	1.5
11	**Average**	**104**	**6**	**4**	**2**
12	**SD**	**44**	**2**	**1**	**1**

As well as the measurable attributes, the smelting slags of Kigonsera are generally greyish or brownish with the majority exhibiting flow texture or flow marks indicative of tap slags. The possession of clear flow marks of the slags, the lack of slag-pit

provisions within the furnaces as well as the lack of substantial evidence of droplet slags support (cf. Table 7.2 and Table 7.3) the slag-tapping process proposal for this area. Nevertheless, if slag tapping was indeed practised as verified by microstructural data as well (see below), then the liquid slag was not tapped through tuyères, as tuyère-mould slags are yet to be recovered from Kigonsera area. It may be that the slag was tapped through a tunnel as was with the *vintengwe* refining furnaces (e.g. Greig 1937; Wise 1958; Brock and Brock 1965), or alternatively through a small hole at the bottom of the tuyère level (e.g. Schmidt 2006: 159). Finally, unlike the rough and magnetic Ntuha slags, the smelting slags of Kigonsera have relatively low magnetism, which is in agreement with the fact that they were generally also less corroded.

Besides the smelting slags, one smithing site (ST4) with typical smithing slags has also been discovered from the Kigonsera area. Three types of slag were present at the site, namely scales, droplets and agglomerated slags (Figure 7.8). In addition to the slag, there was an anvil with dolly holes at this site, but hammers were not recovered probably due to their portable nature. These types of materials as well as smithing cake slags make the area an incontrovertible smithing site. It is noteworthy that the smithing droplets are hollow as opposed to the solid smelting droplet slags (see Miller and Killick 2004).

Figure 7.8: Smithing slags from Mkulusi site #4: hammer scales (right), droplet slags (middle), and agglomerated smithing slags (left)

7.2.5 Pottery

7.2.5.1 Pottery from Lituhi ward

About 17 potsherds were retrieved from the re-excavation of the Ntuha (IiJc-4) site, but unfortunately, all of these were undecorated. It is noteworthy that decorated pottery has been discovered by others (see Mapunda and Burg 1991), and based on their decorative motifs as well as morphological attributes, the Ntuha pottery is similar to the Tana or TIW tradition (Mapunda and Burg 1991; Mapunda 1991, 2001). Within the current research, it is appropriate to examine the material science of the pottery as compared to the furnace walls, platform clays and tuyères, in order to determine whether or not the iron smelters at Ntuha were selecting clay for specific metallurgical purposes (e.g. Freestone and Tite 1986; Childs 1989b).

7.2.5.2 Pottery from Kigonsera ward

Decorated and undecorated pottery was found at Kigonsera ward. The pottery of Mkulusi site #1 is decorated with even, simple lines (Figure 7.9), but that retrieved from Mkulusi site #7 is decorated with open triangles connected to a straight line (Figure

7.10). There are several decorative motifs found on pottery from Matalawe site 8, which include pottery with wavy marks, zigzag lines, evenly spaced straight lines and indent decoration (Figure 7.11). The pottery at Minazi site 4 was decorated with cross hatches and zigzag lines (Figure 7.12). Unfortunately, it has been difficult to compare the pottery of this area to the pottery of other areas of the country or elsewhere. The pottery from this area is yet to be dated, but it looks relatively recent. Based on the archaeological context, where most of the pottery from Kigonsera (and Ntuha) is directly associated with the ironworking remains, it is possible to state that they may have been used for iron smelting purposes or for other smelters' personal uses.

Figure 7.9: Photograph of the decorated pottery from Mkulusi smelting site 1

Figure 7.10: Photograph of the decorated pottery from Mkulusi smelting site 7

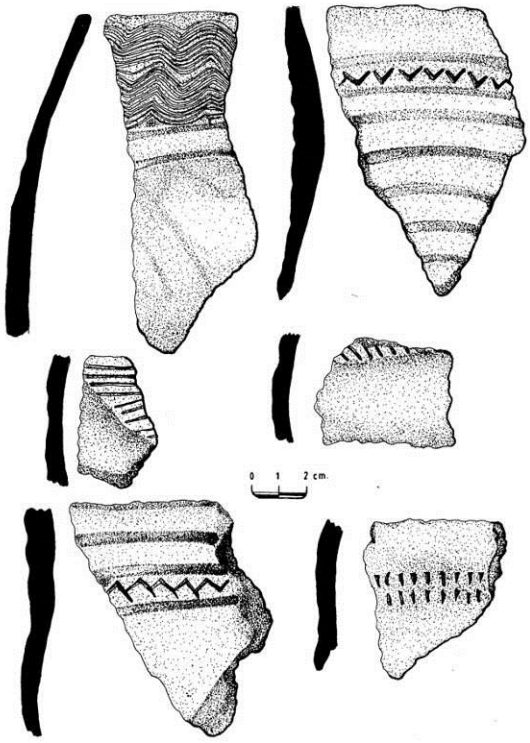

Figure 7.11: Sketch of the decorated pottery from Matalawe pottery site 8

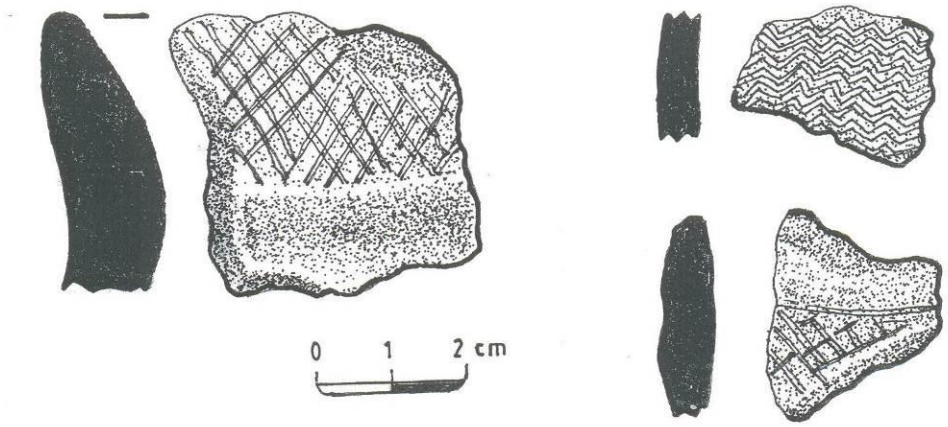

Figure 7.12: Sketch of the decorated pottery from Minazi pottery site 4

7.3 Presentation and Interpretation of Microscopic Data

7.3.1 Technical Ceramics Chemical Data

7.3.1.1 Technical ceramics from Ntuha (IiJc-4) site

The major and minor element concentrations in the technical ceramics from Ntuha are presented below (see Table 7.13). On average, there is a higher concentration of alumina, iron, lime, magnesia, titania, soda, and vanadia in the platform (PLT) than in the furnace wall (FW) samples. Also, there is relatively lower concentration of silica and potash in the platform than in the furnace wall samples. Based on this, it can be argued that the clays selected for the construction of the platforms and the smelting furnaces at the Ntuha site were different chemically.

On the other hand, soda, magnesia, and lime are on average present in relatively higher concentrations in the tuyères (TYR) than in the pottery (PTR) samples. In addition, the alumina, sulphide, potash, titania, and iron oxides are in lower concentrations in the tuyères than in the pottery samples. This subtle but systematic difference can be used to

propose that the clays used to manufacture the tuyères and pottery at the Ntuha site might have come from a different geological source.

Table 7.13: (P) XRF-EDS Major and minor element concentrations of the technical ceramics from Ntuha site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.6; FW=furnace wall, PLT=platform, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
1	FW1	0.26	1.21	16.12	74.52	0.01	1.99	1.58	0.88	0.01	0.19	3.23	99.91
2	FW2	0.28	1.14	15.26	75.70	0.01	1.98	1.79	0.82	0.00	0.18	2.85	99.91
3	SFW3	0.25	0.59	17.83	75.21	0.04	2.06	0.18	0.77	0.00	0.07	2.99	99.57
4	SPLT1	0.99	2.98	22.15	57.66	0.00	1.06	4.04	1.23	0.03	0.14	9.72	99.76
5	SPLT2	1.03	3.03	21.76	58.76	0.00	1.07	3.89	1.14	0.03	0.12	9.18	99.00
6	SPLT3	0.79	2.58	22.16	58.43	0.00	2.31	3.43	1.10	0.02	0.11	9.05	100.40
7	1TYR1	0.29	0.65	12.96	78.93	0.01	1.79	1.41	0.68	0.01	0.18	3.10	100.67
8	2TYR2	0.34	0.76	17.71	75.66	0.02	1.63	0.42	0.71	0.00	0.09	2.66	98.89
9	3TYR3	0.27	0.57	17.86	76.02	0.03	1.55	0.40	0.71	0.01	0.10	2.48	99.12
10	2PTR1	0.22	0.34	17.73	75.90	0.03	1.89	0.13	0.80	0.00	0.07	2.89	99.65
11	1PTR2	0.21	0.37	16.32	77.55	0.03	1.80	0.17	0.73	0.00	0.07	2.75	99.89
12	2PTR3	0.26	0.37	16.56	77.23	0.04	1.81	0.13	0.74	0.00	0.07	2.80	99.70

In terms of the trace elements, there are higher concentrations of copper, tin, and barium oxides in the platform samples than in the furnace wall samples (Table 7.14). In addition, oxides including zinc, rubidium, strontium, zirconium, cerium, and lead are relatively less concentrated in the platform daubs than in the furnace walls. Thus, it is apparent that the smelters at Ntuha selected different clays for the construction of the smelting furnaces and the supposedly charging platforms.

Similarly, all trace element concentrations point to two possible different clay sources used for the manufacturing of the tuyère and pottery samples. For example, cobalt, nickel, zinc, gallium, strontium, and barium oxides measure relatively less in the tuyères than in the pottery. Also, copper, rubidium, yttrium, zirconium, lanthanum, cerium, hafnium, tungsten, lead, and thorium oxides are in higher concentrations in the tuyères

than in the pottery samples. Based on the data, the clays for the manufacturing of the tuyères and the pottery at Ntuha were collected from a separate geo-chemical source.

Table 7.14: (P) XRF-EDS Trace element concentrations (in ppm) of the technical ceramics from Ntuha site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.7; FW=furnace wall, PLT=platform, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	SnO_2	Ba	La	Ce	Hf	Ta_2O_5	WO_3	PbO	Th
1	1FW1	39	14	47	30	7	53	75	22	229	3	271	10	30	10	6	63	29	15
2	2FW2	37	12	145	28	6	49	82	21	245	11	386	10	30	11	9	74	31	14
3	SFW3	31	12	121	27	7	42	30	18	193	9	312	7	21	8	9	33	22	14
4	SPLT1	32	11	225	24	6	38	26	18	207	17	336	9	21	11	12	49	22	13
5	SPLT2	34	11	168	24	6	39	36	17	188	12	447	7	22	10	9	49	21	12
6	SPLT3	37	12	183	23	7	39	27	19	207	14	364	7	19	9	10	79	23	13
7	1TYR1	37	10	99	24	8	46	67	19	242	8	182	13	26	11	7	170	20	14
8	2TYR2	34	16	74	22	7	37	31	17	246	6	140	11	25	11	8	92	21	13
9	3TYR3	28	12	84	24	7	34	32	18	249	7	159	13	29	11	8	71	24	14
10	2PTR1	127	53	22	67	14	17	297	14	54	1	254	9	16	4	6	27	7	2
11	1PTR2	66	53	81	64	14	17	272	14	57	6	276	11	11	6	8	23	6	3
12	2PTR3	61	29	85	56	15	42	422	11	84	3	491	8	17	6	8	11	12	4

To summarise the results from the technical ceramics of the Ntuha site, Figure 7.13 below shows that the chemical differences between the clays used for the construction of the furnaces and platform can also be demonstrated on the basis of refractory quality. The furnace clays were more refractory than the platform clays. This was not unexpected, for the smelting furnaces were exposed to much higher temperatures than the platform. For the same reasons, the platform is also less refractory than the tuyères and pottery. In addition, Figure 7.13 illustrates that despite the possible chemical differences between the tuyères and pottery samples, they have similar refractory properties, close to that of the smelting furnaces.

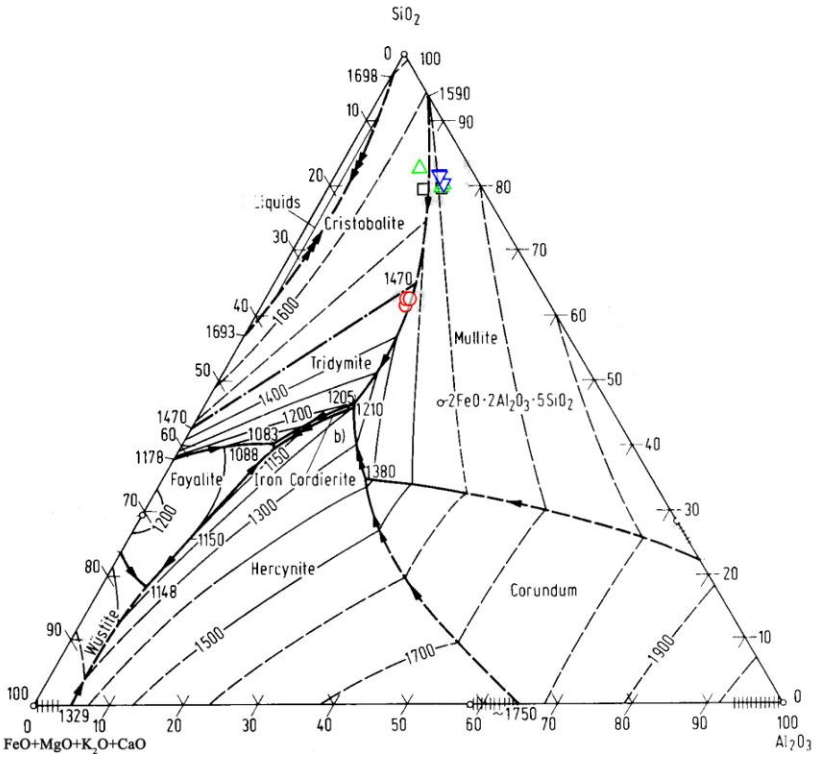

Figure 7.13: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Ntuha site. The circles (red) are platform, the squares (black) are furnaces, the upward triangles (green) are tuyères, and the downward triangles (blue) are pottery samples.

7.3.1.2 Technical ceramics from Mkulusi smelting site #1

Table 7.15 presents major and minor oxide compositions of the furnace walls (FW), tuyères (TYR), and pottery (PTR) samples from this site. On average, tuyères have much higher concentrations of silica and potash than furnace walls and pottery samples. Also, there is more alumina, lime, soda, and magnesia in the pottery than in the tuyères and furnace walls. Moreover, furnace walls have higher concentrations of iron, titanium, and manganese oxides than tuyères and pottery samples (see Table 7.15). Based on these differences, the smelters at this site used certain clays to build the furnaces, but chose different clay to manufacture the tuyères. Clays used to produce pottery were perhaps different as well.

Table 7.15: (P) XRF-EDS major and minor concentrations of the technical ceramics from Mkulusi #1 site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.8; FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
1	1FW1	0.08	0.40	24.67	57.86	0.03	1.85	0.40	2.10	0.03	0.23	12.34	103.63
2	1FW2	0.09	0.51	23.86	59.29	0.02	1.65	0.58	2.12	0.04	0.21	11.61	103.34
3	1FW3	0.11	0.39	26.05	57.09	0.02	1.82	0.39	2.05	0.04	0.19	11.85	102.82
4	1TYR1	0.28	0.42	19.78	70.56	0.03	2.33	0.28	2.83	0.03	0.06	3.41	99.86
5	1TYR2	0.20	0.53	22.76	69.77	0.02	3.05	0.19	1.05	0.02	0.03	2.39	98.61
6	1TYR3	0.18	0.44	21.03	69.46	0.03	1.09	0.29	1.71	0.03	0.05	5.70	100.54
7	1PTR1	0.59	0.44	34.90	54.57	0.00	0.76	5.09	0.48	0.00	0.02	3.14	95.40
8	1PTR2	0.88	0.56	32.16	55.83	0.00	0.64	6.09	0.51	0.01	0.02	3.29	95.20
9	1PTR3	0.74	0.62	32.60	55.29	0.00	0.69	6.14	0.52	0.00	0.02	3.37	95.71

The possibility that the smelters at Mkulusi #1 site could have intentionally selected different clays for different technical ceramics is also supported by the differences between the three ceramics in the trace element concentrations (Table 7.16). On average, there are higher concentrations of cobalt, nickel, zinc, rubidium, yttrium, and lead oxides in the furnace walls than in the tuyères and pottery samples. There are also

higher concentrations of copper, zirconium, barium, cerium, hafnium, tungsten, and thorium oxides in the tuyères than in the furnace walls and pottery samples. Furthermore, there is more strontium by about 330 ppm in the pottery samples than in the furnace wall and tuyère samples. Based on these differences, it is apparent that there was intentional selection of clays for different technical purposes.

Table 7.16: Trace oxide (P) XRF-EDS bulk compositions of the technical ceramics from Mkulusi #1 site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.9; FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	SnO_2	Ba	La	Cerium	Hf	Ta_2O_5	WO_3	PbO	Th
1	1FW1	107	43	113	251	15	55	24	34	181	11	7	109	24	42	7	8	38	64	11
2	1FW2	120	32	98	67	16	48	30	34	179	12	4	110	20	40	7	9	43	56	12
3	1FW3	129	37	87	61	15	56	26	34	189	11	4	105	22	39	8	14	6	18	12
4	1TYR1	53	27	136	41	11	39	26	32	500	12	11	139	31	64	22	9	146	19	32
5	1TYR2	31	28	163	35	12	71	31	25	120	5	12	208	22	63	8	10	144	29	26
6	1TYR3	60	38	58	42	12	29	17	21	155	9	2	77	12	30	6	6	56	17	15
7	1PTR1	30	10	26	16	13	12	301	6	28	2	1	139	6	8	4	4	28	6	3
8	1PTR2	31	10	18	17	13	8	333	5	25	2	1	131	6	8	3	4	66	4	2
9	1PTR3	28	11	11	18	13	8	358	4	26	3	1	145	6	9	3	3	57	5	2

To sum up on the technical ceramics of this site, the pottery and tuyères had similar refractory properties (Figure 7.14). Although they are similar, there is more alumina in the pottery than in the tuyères, which had more silica than the pottery. The chemical difference, it can be argued, makes the tuyères more dimensionally stable to heat shock and temperature fluctuations than the pottery (Freestone and Tite 1986). In addition, both the tuyères and pottery are more refractory than the furnace wall samples. The difference in refractory quality between the tuyères and furnace walls was not unexpected, because the former are subjected to higher temperatures than the latter (Freestone and Tite 1986).

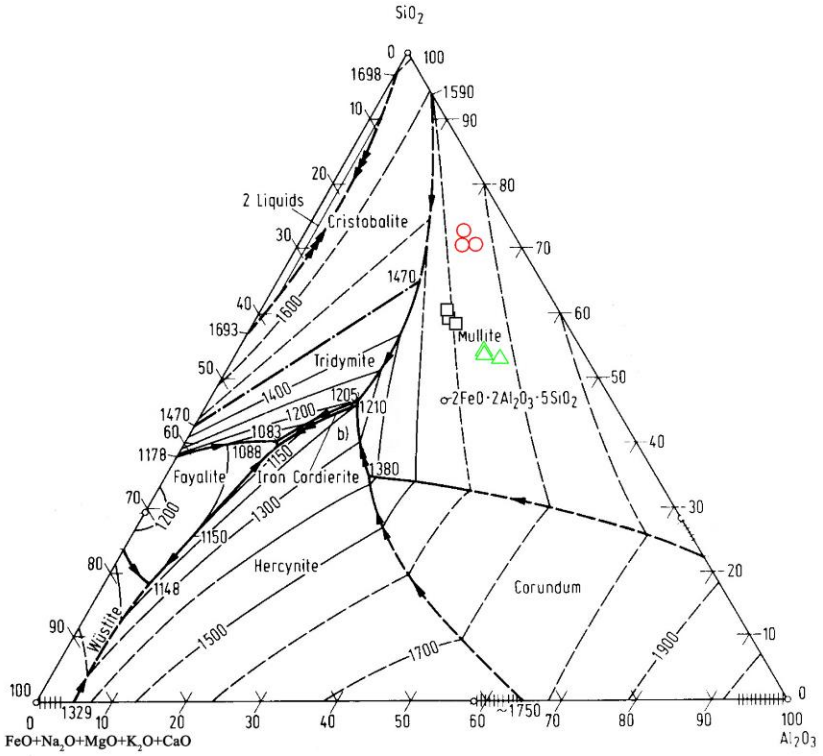

Figure 7.14: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Mkulusi #1 site. The squares (black) represent the furnace walls, the circles (red) are tuyères, and the upward triangles (green) represent the pottery

7.3.1.3 Technical ceramics from Mkulusi smelting site #7

Table 7.17 presents major and minor oxide compositions of the technical ceramics from Mkulusi site #7. There are differences between the three sets of samples. For example, on average, the tuyères have higher concentrations of silica, potash, and magnesia than the furnace walls and pottery samples. Also, there is a higher concentration of alumina, lime, and soda in the pottery than the furnace walls and tuyères. Furthermore, the furnace walls have higher concentrations of iron, titania and manganese oxides than tuyères and pottery samples. Based on the differences in major and minor oxide concentrations, it can be argued that the iron smelters at this site used different clays for the construction and manufacturing of the technical ceramics. This interpretation is supported by the differences in trace oxide data as well (Table 7.18). On average, the furnace walls have higher concentrations of cobalt, nickel, copper, zinc, yttrium, zirconium, niobium, lanthanum, and tungsten oxides than the tuyères and pottery samples, and the tuyères have higher concentrations of rubidium, barium, cerium, lead, and thorium oxides than the furnace walls and pottery samples.

Table 7.17: (P) XRF-EDS major and minor oxide concentrations of the technical ceramics from Mkulusi #7 site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.10; FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
1	1FW1	0.17	0.84	21.14	62.41	0.03	2.35	0.60	1.98	0.04	0.20	10.25	103.32
2	1FW2	0.20	0.36	16.71	70.38	0.03	1.49	0.22	1.89	0.03	0.09	8.60	104.13
3	1FW3	0.26	0.36	14.67	72.22	0.02	1.40	0.21	1.68	0.03	0.10	9.05	103.83
4	1TYR1	0.19	0.95	24.13	67.40	0.02	3.67	0.33	0.77	0.02	0.03	2.49	98.82
5	1TYR2	0.16	0.62	25.20	66.63	0.02	3.40	0.33	1.04	0.02	0.04	2.55	98.86
6	1TYR3	0.21	0.61	23.59	69.21	0.03	2.99	0.21	1.02	0.02	0.03	2.09	98.70
7	1PTR1	1.00	0.73	28.92	59.12	0.00	1.30	5.70	0.42	0.01	0.03	2.77	96.46
8	1PTR2	0.66	0.72	30.42	55.64	0.00	0.72	4.93	0.99	0.02	0.04	5.86	97.49
9	1PTR3	0.65	0.48	32.94	55.84	0.00	1.11	5.44	0.48	0.01	0.03	3.03	96.04

Table 7.18: (P) XRF-EDS Trace oxide concentrations of the technical ceramics from Mkulusi #7 site. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 7.11; FW=furnace wall, TYR=tuyère, and PTR=pottery

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	WO_3	PbO	Th
1	7FW1	124	50	61	62	14	71	36	39	185	12	188	20	42	61	22	14
2	7FW2	61	35	97	44	11	40	20	28	189	11	115	21	38	99	16	14
3	7FW3	66	32	43	46	9	40	16	26	165	11	100	19	35	72	8	12
4	7TYR1	40	19	26	27	11	74	35	22	113	5	215	14	36	86	22	15
5	7TYR2	38	28	42	33	12	74	41	23	136	5	242	14	43	73	26	18
6	7TYR3	26	18	20	26	11	61	30	25	149	7	209	21	60	50	27	25
7	7PTR1	20	8	8	17	10	22	377	4	27	2	128	6	8	23	5	3
8	7PTR2	45	15	22	27	13	13	359	4	20	2	88	6	8	82	6	2
9	7PTR3	30	14	18	12	14	20	401	4	10	2	141	6	8	25	5	3

The above explained difference in the clays carefully selected for the construction and manufacturing of the technical ceramics at the Mkulusi site #7 becomes apparent when some of the major oxides are plotted on a ternary phase diagram (Figure 7.15).

Similarly to the ceramics of the Mkulusi site #1, although all three sets of data plot at different positions, the pottery and tuyères of Mkulusi site #7 have similar refractory quality. Perhaps the tuyères with more silica were more dimensionally stable to heat shock and temperature fluctuation than the pottery. In addition, both the pottery and tuyères are clearly more refractory than the furnace walls.

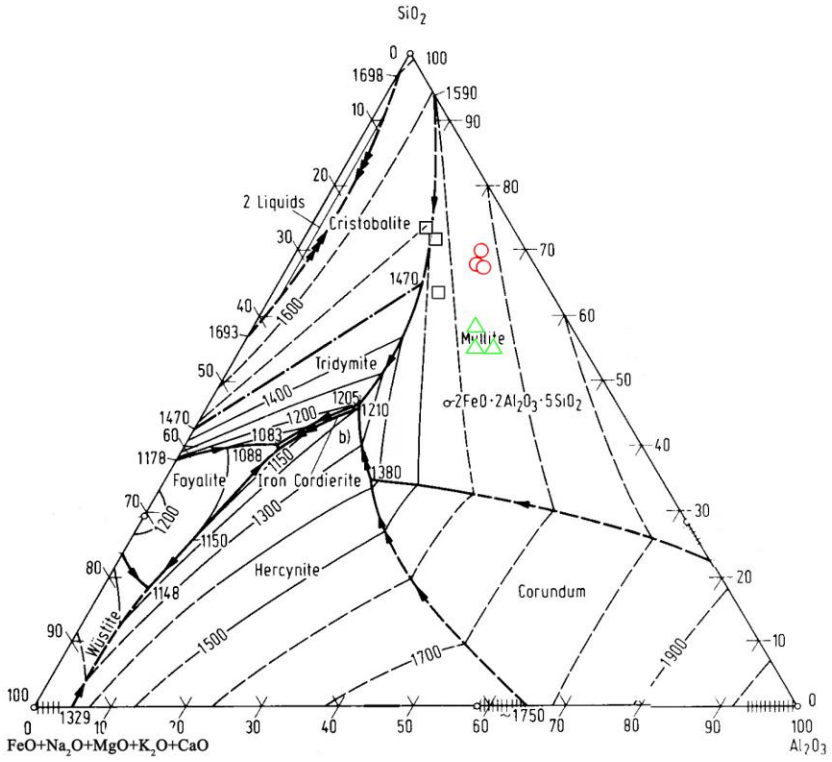

Figure 7.15: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Mkulusi #7 site. The squares (black) represent the furnace walls, the circles (red) are tuyères, and the upward triangles (green) represent the pottery.

7.3.2 Smelting Slag Chemical Data

Early researchers in Umatengo have, based on archaeological data alone, likened the ancient ironworking of north-eastern Umatengo to the recent ironworking of the other parts of Umatengo (e.g. Mapunda 1991: 7, 69; 2001: 108). The current research project is designed to test such assumptions based on archaeometallurgical data including chemical and microstructural examination, especially of the smelting slags. To this end, and to enable the comparison of the Ntuha (ancient) and Mkulusi site #1 and #7 (recent) sites, the smelting slags from the respective sites are presented and discussed jointly (Table 7.19). Based on the data, the recent slags from Mkulusi site #1 and #7 sites are similar in terms of major and minor oxides (see Table 7.19) as well as trace oxide concentrations (see Table 7.20). The similarity of the two sites in the major ore indicators such as alumina, phosphorus, titania, manganese, and barium points to the

possibility of using a similar ore. Likewise, the similarity could indicate a more standardized technology operating at a fully-fledged stage by highly skilled and experienced smelters, although I have no ethnoarchaeological data to claim that these two sites were controlled by one chief smelter.

The ancient Ntuha slags have relatively more iron oxide (about 66 wt% on average) than the Mkulusi site #1 and #7 slags, which have about 44 and 43 wt% FeO respectively. Also, the slags from the Ntuha site contain relatively lower alumina and silica concentrations than the slags from Mkulusi site #1 and #7 sites. Because of these differences, the Ntuha slags have relatively low alumina to silica ratios of about 1:3, and the Mkulusi site #1 and #7 slags have a ratio of about 1:5 each. If the semi-bulk composition (disregarding unreacted quartz and metal prills) (see Appendix 7.12) of the three major oxides (CaO and MnO proportionally adjusted in relation to the molecular weight of FeO and added to FeO in order to sum up to or well above 95 wt% before normalization) are plotted on a ternary phase diagram (Figure 7.16), the proposed difference becomes even more apparent. Figure 7.16 shows that most of the slags from the Ntuha area plot in the lower fayalite region and the wüstite region, while the Mkulusi slags plot in the upper fayalite region and the tridymite region. In other words, the slags from the Ntuha site more or less plot close to the least efficient process zone, optimum 2 (Rehren *et al*. 2007: 212), while the Mkulusi slags more or less plot close to the most efficient process zone, optimum 1 (Rehren *et al*. 2007: 212).

Table 7.19: SEM-EDS major and minor oxide concentrations of the smelting slags from Ntuha, Mkulusi site #1, and #7 sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 7.13

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	BaO	Total
Smelting slags from Ntuha													
1	2SE1	0.3	0.7	9.4	27.4	0.4	1.9	3.5	0.2	3.8	53.2	0.4	101.2
2	2SE2	0.0	0.5	6.3	13.9	0.3	0.8	3.7	0.3	3.2	71.7	0.0	100.6
3	2SE3	0.1	0.7	2.8	7.8	0.1	0.3	0.6	0.1	2.3	85.0	0.1	100.0
4	1SE4	0.1	0.7	6.4	26.2	0.3	0.7	1.2	0.2	3.1	60.6	0.2	100.0
5	SSE5	0.1	0.5	6.3	27.5	0.1	1.1	1.1	0.1	3.7	59.4	0.3	100.2
Smelting slags from Mkulusi site #1													
6	1SE1	0.0	0.9	10.0	44.6	0.5	2.0	2.3	1.1	0.9	37.5	0.1	100.0
7	1SE2	0.0	0.6	7.8	43.9	0.4	1.4	2.4	1.3	0.1	41.9	0.0	100.0
8	1SE3	0.1	0.7	8.3	38.3	1.0	1.2	3.6	1.1	0.2	45.4	0.1	100.0
9	1SE4	0.1	0.6	7.9	41.9	0.5	1.3	2.2	1.3	0.1	44.4	-0.1	100.0
10	1SE5	0.1	0.4	5.0	44.5	0.5	1.1	1.5	1.0	0.1	45.6	0.1	100.0
Smelting slags from Mkulusi site #7													
11	7SE1	0.0	0.7	7.6	41.2	0.5	1.2	4.7	0.9	0.2	42.8	0.1	100.0
12	7SE2	0.1	0.9	7.6	40.7	0.8	1.6	2.7	0.9	0.2	44.5	0.1	100.0
13	7SE3	0.0	0.6	7.5	43.8	0.5	1.4	1.6	1.3	0.1	43.3	-0.2	100.0
14	7SE4	0.0	1.1	7.1	40.6	1.0	1.7	3.1	1.1	0.1	44.3	-0.1	100.0
15	7SE5	0.0	0.9	7.6	40.2	0.9	1.7	2.9	0.9	0.1	44.4	0.2	100.0

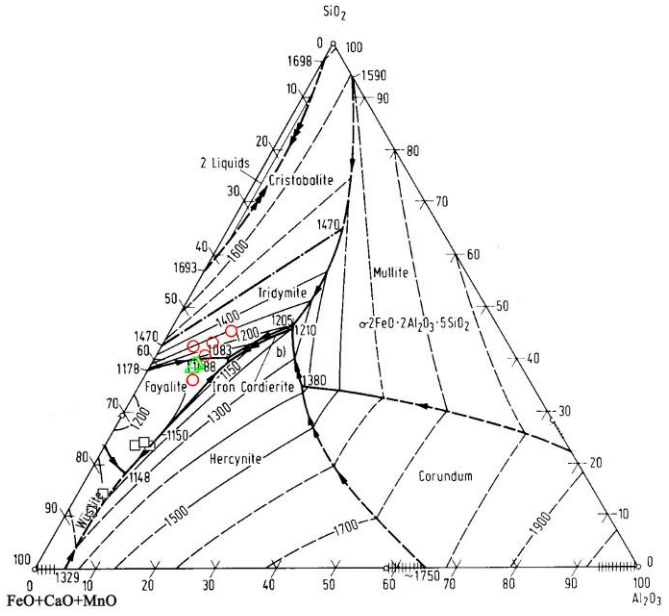

Figure 7.16: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting slags from Ntuha (black squares), Mkulusi site #1 (green triangles), and Mkulusi site #7 (red circles)

The key questions that relate to the phase diagram are: (1) can we explain the factors that might have contributed to the evident chemical difference, and (2) can we understand the nature of the product smelted at the two areas (Ntuha and Mkulusi) based on the diagram alone? One of the key factors that could have made a difference was the effect of the fuel to ore ratio at the two (Ntuha and Mkulusi) areas. With the exception of soda, it appears that the Ntuha slags have lower concentrations of fuel ash indicators than the slags from the Mkulusi area (see Table 7.19). If other factors kept constant, the apparently higher fuel to ore ratio at the Mkulusi sites would increase the CO/CO_2 ratio to enable more reduction of the iron from the ore gangue and potentially resultant in comparatively lean slags (Tylecote *et al*. 1971; Killick and Gordon 1989; Rehren *et al*. 2007). While this is likely to have been the case, alternatively it could have been the effect of the smelted ore.

The difference in concentration of the major ore indicators – which will not be reduced into the metal during the smelting process and hence are expected to be seen in the resultant slags (Severin *et al*. 2011) – between the two sets of slags points to a possibility that two different ores were smelted at the two areas. On average, the Ntuha slags contain more manganese oxide (about 3.2 wt%) than the slags from Mkulusi which have less than 0.3 wt% manganese oxide. Also, there is less titania (about 0.2 wt%) and more barium oxides (about 0.2 wt%) in the former, while the latter have around 1 wt% titania and have almost no barium oxide in them. As well as the difference in manganese, titania, and barium, the two sets of slags are chemically different in their trace oxide concentrations (Table 7.20). For example and on average, there is a higher concentration of cobalt, nickel, strontium, and thorium in the Ntuha slags than in the slags from the Mkulusi sites. Also, there is more zirconium, cerium, and tungsten in the Mkulusi slags than in the Ntuha slags. While the rest of the trace

elements show no difference, based on the differences in the non-reducible compounds (NCRs) (Severin *et al*. 2011), the ironworkers at the Ntuha site smelted a different ore from that smelted at the Mkulusi area. It is unclear whether the proposed difference in the smelted ores contributed to the difference observed in the resultant slags especially in the FeO concentration, but we know smelting a very rich ore or a very lean ore could result in variation of FeO concentration (Tylecote *et al*. 1971: 252). In this respect, and with other factors kept constant, it is possible that the Ntuha smelters worked with an iron rich ore, and smelters at Mkulusi worked with a leaner ore. In order to produce slag with the former, more iron oxide was required to combine with (less) gangue material to form slag, while with the latter little iron oxide combined with (more) gangue to form slag.

Table 7.20: (P) XRF-EDS Trace oxide concentrations of the smelting slags from Ntuha, Mkulusi site #1, and #7 sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 7.14

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	SrO	Y	ZrO_2	Nb_2O_5	Ba	Ce	Hf	Ta_2O_5	WO_3	Th	U	Analytical total
Smelting slags from Ntuha																	
1	2SE1	150	10	14	9	269	38	20	8	619	12	11	10	17	13	10	1209
2	2SE2	190	15	20	7	80	19	5	7	225	12	16	16	27	21	12	673
3	2SE3	183	16	20	6	86	19	8	8	340	12	16	18	23	20	12	789
4	1SE4	160	13	24	20	186	31	6	7	385	12	13	14	20	15	11	917
5	SSE5	160	11	14	23	269	26	50	6	801	12	13	12	16	14	11	1439
Smelting slags from Mkulusi site #1																	
6	1SE1	109	6	18	7	74	25	122	9	554	74	8	8	89	6	9	1118
7	1SE2	110	7	18	6	68	22	153	5	91	31	9	9	85	7	8	629
8	1SE3	120	9	34	9	80	25	94	9	71	26	12	25	25	9	9	556
9	1SE4	149	7	20	7	63	22	139	8	80	29	10	12	14	8	10	577
10	1SE5	117	8	21	11	41	24	130	4	67	38	10	13	13	8	11	516
Smelting slags from Mkulusi site #7																	
11	7SE1	110	8	34	9	144	24	78	13	90	39	10	14	65	7	9	654
12	7SE2	120	8	18	5	81	25	101	7	77	45	10	10	84	8	12	610
13	7SE3	120	8	15	6	56	25	99	7	77	35	10	11	47	9	9	535
14	7SE4	116	7	19	4	88	26	109	8	82	46	10	12	27	8	9	572
15	7SE5	110	7	20	3	86	25	104	7	80	44	10	10	45	8	9	569

7.3.3 Smelting Slag Mineralogical Data

The microstructures of the smelting slags from the Ntuha and Mkulusi areas are presented jointly, in order to compare the technological processes of the two areas. To this end, each of the phases (Table 7.21) is first examined and discussed alone, starting with fayalite through the quartz grains.

Table 7.21: Summary of phases of the smelting slags from Ntuha and Mkulusi site #1 and #7 sites; SE=smelting slag

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Wustite	Magnetite	Tap lines	Hematite	Fe droplets	Fe particles	Leucite	Porosity	Quartz
Smelting slags from Ntuha													
1	2SE1	√	√	√	√	√	-	-	-	-	-	√	√
2	2SE2	√	-	√	√	√	-	-	-	-	-	√	-
3	2SE3	√	-	√	√	√	-	√	-	-	-	√	-
4	1SE4	√	√	√	√	-	?	-	-	√	√	√	-
5	SSE5	√	√	√	√	-	?	√	-	-	-	√	-
Smelting slags from Mkulusi site #1													
6	1SE1	√	-	√	-	-	-	-	√	-	-	√	-
7	1SE2	√	-	√	-	-	-	-	√	-	-	√	-
8	1SE3	√	-	√	-	√	√	-	√	-	-	√	-
9	1SE4	√	-	√	-	-	-	-	√	-	-	√	-
10	1SE5	√	-	√	-	-	-	-	√	-	-	√	√
Smelting slags from Mkulusi site #7													
11	7SE1	√	-	√	-	-	√	-	√	-	-	√	-
12	7SE2	√	-	√	-	-	-	-	√	-	-	√	√
13	7SE3	√	-	√	-	-	√	-	√	-	-	√	√
14	7SE4	√	-	√	-	-	√	-	√	-	-	√	-
15	7SE5	√	-	√	-	√	√	-	√	-	-	√	-

7.3.3.1 Fayalite crystals

All the slags from Ntuha and Mkulusi contained fayalite as would be expected. The Ntuha slags exhibit relatively blocky fayalitic microstructures, while the slags from Mkulusi site #1 and #7 have thin, skeletal and elongated crystals of fayalite (Figure

7.17). The difference in crystal size suggests that the slags at Ntuha site cooled relatively slowly maybe in a slag-pit underneath the furnace, while the slags at the Mkulusi sites cooled rapidly, perhaps outside of the furnace.

In addition, based on the chemical composition of the crystals (Table 7.22) almost all of the slags from Ntuha (except sample SSE5 alone) contained impure fayalitic crystals, while almost all the slags from the Mkulusi sites (except 1SE2, 1SE5, and 7SE4) had pure fayalite crystals with $2FeO.SiO_2$ chemistry. The impure crystals of the Ntuha slags contain MnO that combine with FeO to a ratio of 1:6-15 generally to form fayalitic crystals called knebelite with the formula $2(FeO.MnO).SiO_2$ (Bachmann 1982). In addition, the MgO concentration of sample 7SE4 combines with FeO to a ratio of 1:12 to form fayalitic crystals (Bachmann 1982: 14). It was difficult to measure the composition of the fayalite crystals of samples 1SE2 and 1SE5 from Mkulusi for they were very thin crystals (Figure 7.18). Nonetheless, based on the shape, they are clearly fayalitic minerals. Moreover, the fayalite crystals from the three sites contain other minor oxides including MgO, Al_2O_3, P_2O_5, CaO, K_2O, and TiO_2.

Table 7.22: SEM-EDS chemical composition of fayalite from the Ntuha and Mkulusi sites; SE=smelting slags. Note the results are the average of three spectra and are normalised to 100 wt%; the full results in Appendix 7.15

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
Smelting slags from Ntuha											
1	2SE1	1.1	0.0	31.5	0.1	0.0	1.4	0.0	6.4	59.6	100
2	2SE2	2.2	0.1	31.3	0.1	0.0	2.6	0.0	9.0	54.7	100
3	2SE3	1.9	0.1	31.4	0.0	0.0	0.5	0.0	6.2	60.0	100
4	1SE4	1.6	0.2	31.4	0.2	0.1	1.3	0.0	4.1	61.1	100
5	SSE5	1.7	0.1	30.9	0.3	0.0	0.2	0.0	5.8	61.0	100
Smelting slags from Mkulusi site #1											
6	1SE1	3.2	0.0	31.7	0.1	0.0	0.2	0.1	1.3	63.2	100
7	1SE2	1.0	3.0	37.5	0.3	0.8	1.2	0.8	0.1	55.3	100
8	1SE3	1.3	0.1	30.9	0.0	0.0	0.2	0.1	0.2	67.3	100
9	1SE4	2.1	0.0	31.5	0.1	0.0	0.2	0.2	0.1	65.7	100
10	1SE5	0.7	2.6	42.7	0.3	1.2	1.1	0.6	0.0	50.7	100
Smelting slags from Mkulusi site #7											
11	7SE1	2.5	0.0	32.1	0.1	0.0	0.4	0.1	0.2	64.6	100.0
12	7SE2	2.0	0.0	31.6	0.4	0.0	0.3	0.2	0.2	65.4	100.0
13	7SE3	1.4	0.0	31.0	0.3	0.0	0.2	0.1	0.2	66.9	100.0
14	7SE4	5.1	0.0	31.9	0.3	0.0	0.4	0.1	0.3	62.0	100.0
15	7SE5	1.9	0.1	31.0	0.2	0.0	0.2	0.0	0.2	66.3	100.0

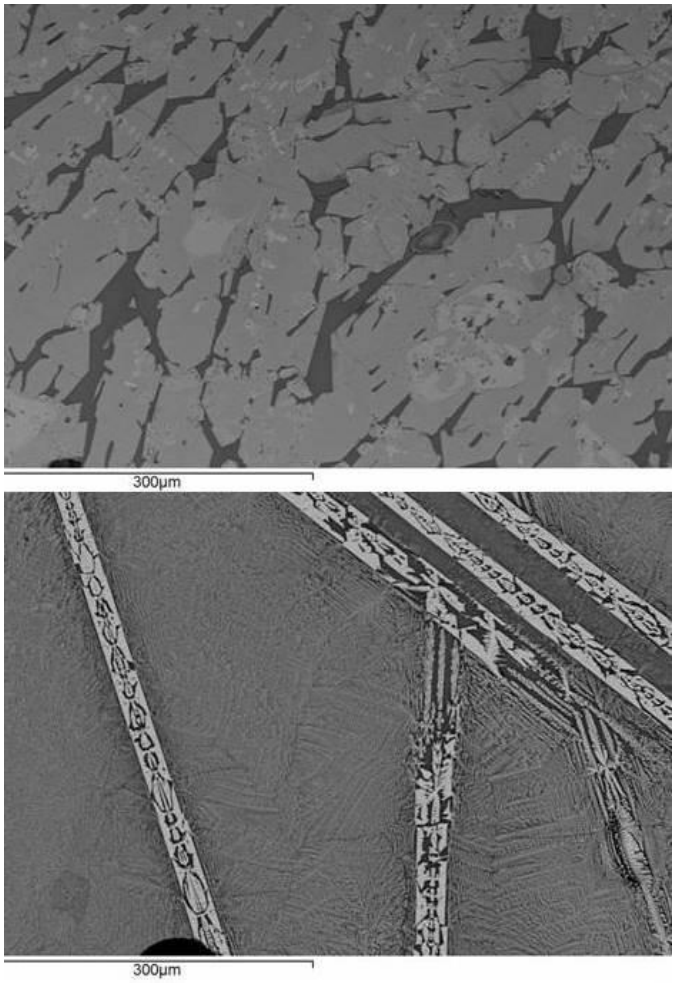

Figure 7.17: SEM-BSE image of fayalitic microstructures of Ntuha (top) and Mkulusi (bottom) smelting slags

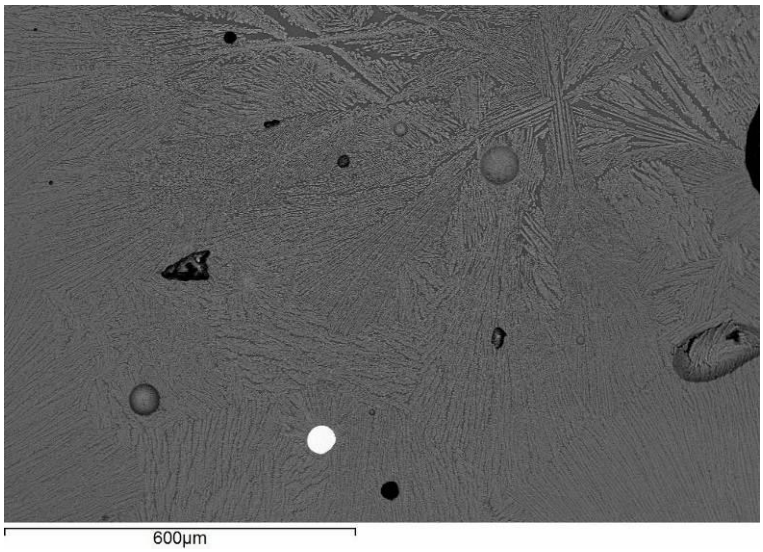

Figure 7.18: SEM-BSE image of the thinnest and most difficult to measure by point analysis fayalitic crystals of the Mkulusi #1 (1SE2)

7.3.3.2 Hercynite crystals

There were three slags alone from the Ntuha area with hercynite crystals (Table 7.23), but it has been difficult to observe any hercynite crystals in the Mkulusi slags. Although in a proper hercynite crystal ($FeO.Al_2O_3$) one should expect relatively more alumina than iron oxide (Anthony *et al*. 1997: 561), the hercynite crystals from this site have a little more FeO and less alumina. This anomaly relates to the fact that there was more than enough FeO in the melt to form hercynite crystals as apparently signalled by the presence of zoned spinels (Figure 7.19). Nonetheless, and based on the 1:1 ratio qualification, they are chemically pure hercynite crystals. Besides the hercynite major oxides, the crystals are also composed of MgO, SiO_2, P_2O_5, V_2O_5, Cr_2O_3, TiO_2, and MnO (see Table 7.23).

Table 7.23: SEM-EDS chemical composition of hercynite crystals from Ntuha smelting (SE) site. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	P_2O_5	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
1	2SE1	1.1	43.3	0.3	0.1	0.7	0.1	0.1	2.2	52.2	100.0
2	1SE4	0.5	49.5	0.5	0.1	0.8	0.0	0.0	1.8	46.7	100.0
3	SSE5	0.3	35.7	0.4	0.0	0.9	0.0	0.0	2.0	62.5	100.9

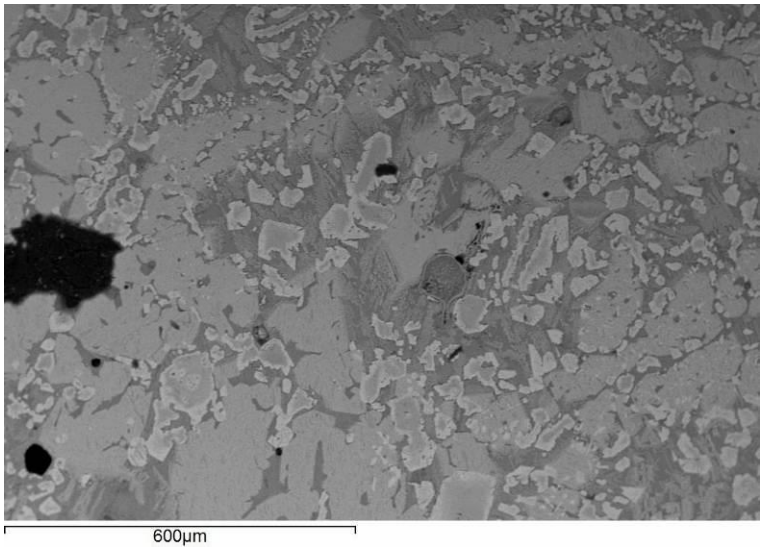

Figure 7.19: SEM-BSE image of some of the zoned hercynite crystals (dark grey) in the Ntuha slags

7.3.3.3 Glass groundmass

There is less volume of glass in the slags of the Ntuha site than in the slags from the Mkulusi sites (Figure 7.20). The difference in volume of the glass is related to the fact that the former slag melt cooled slowly letting the fayalite, hercynite, and wüstite crystals grow thicker and hence occupying more of the volume, while the latter cooled so rapidly that the crystals had less enough time to grow but remained thin and hence occupied a smaller volume of the slag. Major components of the glassy groundmass are SiO_2 and FeO. On average, there are less of these oxides, about 45 and 16 wt% respectively, in the Ntuha slags than in the Mkulusi site #1 and #7 slags (Table 7.24). The latter each respectively contain 48 and 47 wt% silica and 28 wt% iron oxide. With the exception of P_2O_5 and MgO, where the former shows no difference across the two areas and the latter is less concentrated (almost negligible) in the groundmass of the Ntuha slags, the rest of the fuel ash oxides including soda, sulphide, potash, and lime are more concentrated in the glass of the Ntuha slags than in the glass of the Mkulusi slags (see Table 7.24).

The difference in concentration accords the observation above that there is less volume of the glass phase in the Ntuha slags, which made the oxides highly concentrated. Likewise the larger volume of glass in the Mkulusi slags diluted the oxides, hence their low concentrations. In addition, there is relatively more alumina, manganese, and barium oxides in the glass phases of the Ntuha slags than in the glass of the Mkulusi slags (see Table 7.24). The concentration of alumina in the Ntuha slags corresponds with the presence of hercynite crystals. The high concentration of MnO and BaO oxides in them is, as might be expected, related to the nature of the smelted ores.

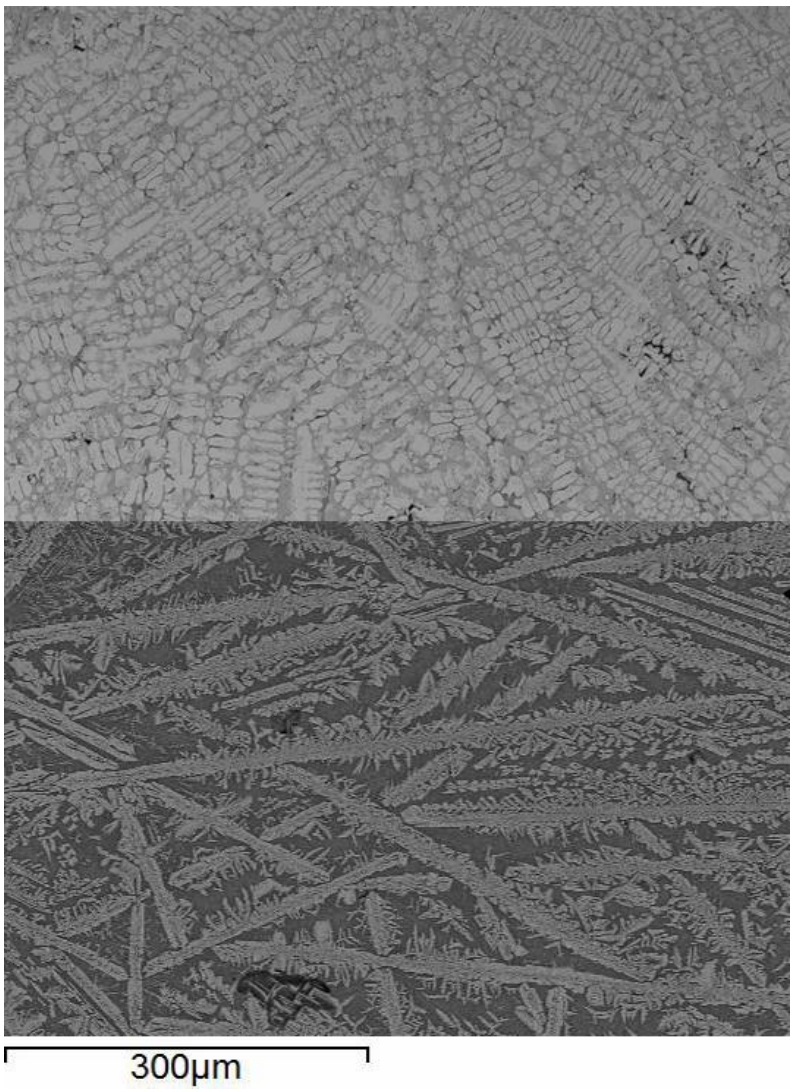

Figure 7.20: SEM-BSE image of little glass volume in the Ntuha slags (top, 2SE3) and more glass volume in the Mkulusi slags (bottom, 7SE5)

Table 7.24: SEM-EDS chemical composition of glass matrix from Ntuha and Mkulusi sites. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	BaO	Total
Smelting slags from Ntuha site														
1	2SE1	0.8	0.0	17.4	39.9	1.2	0.8	7.0	11.2	0.2	1.2	19.1	1.3	100
2	2SE2	0.4	0.0	17.5	37.0	1.9	0.3	4.5	15.0	0.2	1.7	20.6	0.8	100
3	2SE3	1.3	0.0	12.7	44.9	1.9	1.0	9.6	6.5	0.0	1.1	18.7	2.3	100
4	1SE4	0.3	0.0	21.4	52.0	0.1	0.0	17.6	0.3	0.0	0.4	5.7	2.2	100
5	SSE5	0.9	0.1	15.8	53.0	1.0	0.3	6.4	5.9	0.0	1.2	14.6	0.7	100
Smelting slags from Mkulusi site #1														
6	1SE1	0.0	0.3	14.4	49.0	0.7	0.2	2.2	3.8	1.8	0.7	26.7	0.1	100
7	1SE2	0.0	0.1	13.2	49.5	0.6	0.1	1.5	4.5	2.8	0.1	27.4	0.0	100
8	1SE3	0.1	0.1	12.7	42.6	1.4	0.0	1.6	5.8	1.8	0.1	33.5	0.0	100
9	1SE4	0.1	0.1	13.5	48.4	0.9	0.0	1.6	4.3	2.4	0.1	28.5	0.1	100
10	1SE5	0.1	0.0	11.9	51.4	1.3	0.0	1.4	4.6	3.0	0.0	26.1	0.1	100
Smelting slags from Mkulusi site #7														
11	7SE1	0.1	0.1	13.4	47.4	1.0	0.0	2.1	8.3	1.6	0.1	25.9	0.0	100
12	7SE2	0.1	0.1	13.9	47.2	1.3	0.0	2.5	4.9	2.0	0.1	27.7	0.1	100
13	7SE3	0.0	0.2	11.2	45.5	0.8	0.0	1.6	3.3	2.0	0.1	35.2	0.0	100
14	7SE4	0.1	0.2	12.8	47.4	1.3	0.2	2.3	5.4	2.4	0.1	27.8	0.1	100
15	7SE5	0.0	0.1	13.1	48.7	2.1	0.0	3.4	8.2	2.3	0.1	21.7	0.0	100

7.3.3.4 Wüstite crystals

All the slag samples from the Ntuha site had primary wüstite crystals as a dominant phase (Figure 7.21), but none of the slags from the Mkulusi sites contained wüstite crystals. The large size of the wüstite crystals is related to the proposed slow cooling process of the slags in the furnace pit. In addition, the dominance of wüstite in the Ntuha slags corresponds well with the bulk composition, with more FeO than slags from the Mkulusi sites. Based on both the chemical composition and the dominance of wüstite in the slags, the smelters of the Ntuha area wasted relatively more free iron oxides in the slags than the smelters of the Mkulusi area. Other factors kept constant, it may be that the smelters at the Ntuha area were less skilled and experienced to control

the operating parameters so efficaciously that little free iron would have been left in the slags than those smelters at the Mkulusi sites. Moreover, the wüstite crystals on average contained about 96 wt% FeO, 2 wt% MnO, 0.7 wt% alumina, and SiO_2, TiO_2, and MgO all below 1 wt% (Table 7.25).

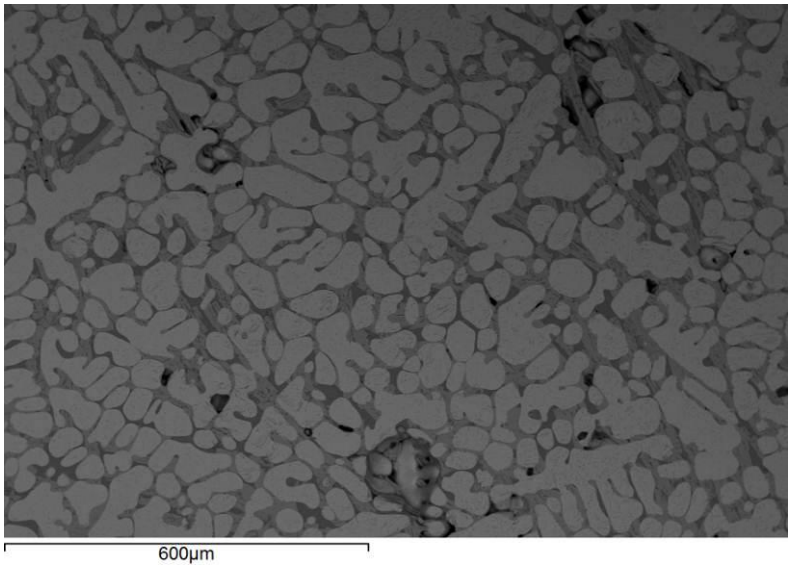

Figure 7.21: SEM-BSE image of wüstite crystals dominant in the Ntuha slags (2SE3)

Table 7.25: SEM-EDS chemical compositions of wüstite crystals from Ntuha site; SE=smelting slag

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	TiO_2	MnO	FeO	Total
1	2SE1	0.0	1.0	0.6	0.7	1.6	96.1	100.1
2	2SE2	0.4	1.5	0.4	0.2	2.6	95.0	100.2
3	2SE3	0.1	0.1	0.7	0.0	1.9	97.1	99.9
4	1SE4	0.1	0.1	0.3	0.5	1.8	96.8	99.6
5	SSE5	0.0	0.7	0.4	0.1	2.0	97.2	100.3

7.3.3.5 Magnetite crystals

Of the samples from the Ntuha site, three out of five had primary magnetite crystals, but only two samples (one from each of the Mkulusi sites) contained secondary magnetite

crystals (Table 7.26). As with the other crystals described earlier, the former are thick crystals (Figure 7.22) easily observed. The latter are very thin crystals that are difficult to identify except at high magnification (about 3000 times). The large size of the magnetite crystals in the Ntuha slags indicates that they cooled slowly in the furnace pit, while those seen in the Mkulusi slags cooled relatively very quickly. The presence of primary high free iron oxides such as magnetite in the slags from Ntuha site suggests an incomplete reduction of the iron metal from the slag, which in turn can be used to support the idea that the smelters working at the site were less skilled and experienced, assuming that other factors are kept constant. On the other hand, the absence of wüstite in most of the Mkulusi slags can be used to argue that the formation of the rare, thin magnetite crystals confined in one area (Figure 7.23) was due to accidental secondary oxidation outside the furnace.

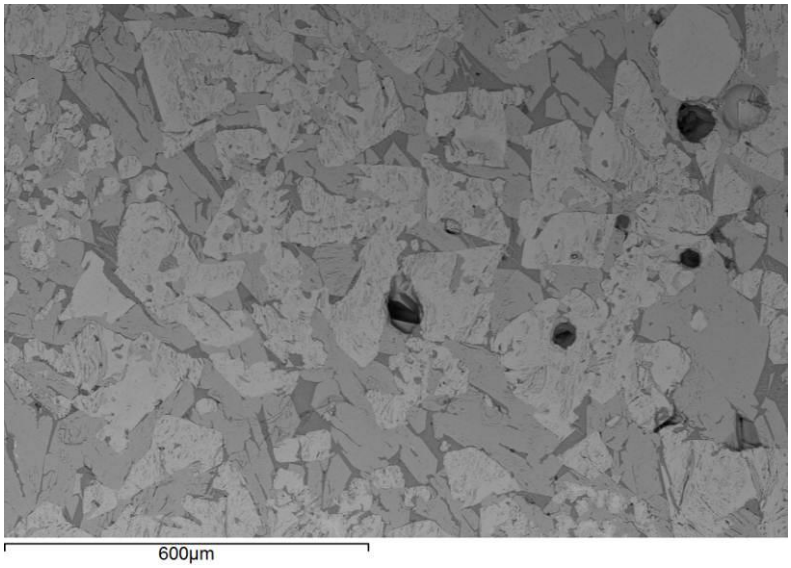

Figure 7.22: SEM-BSE image of primary magnetite crystals in the Ntuha slags (2SE3)

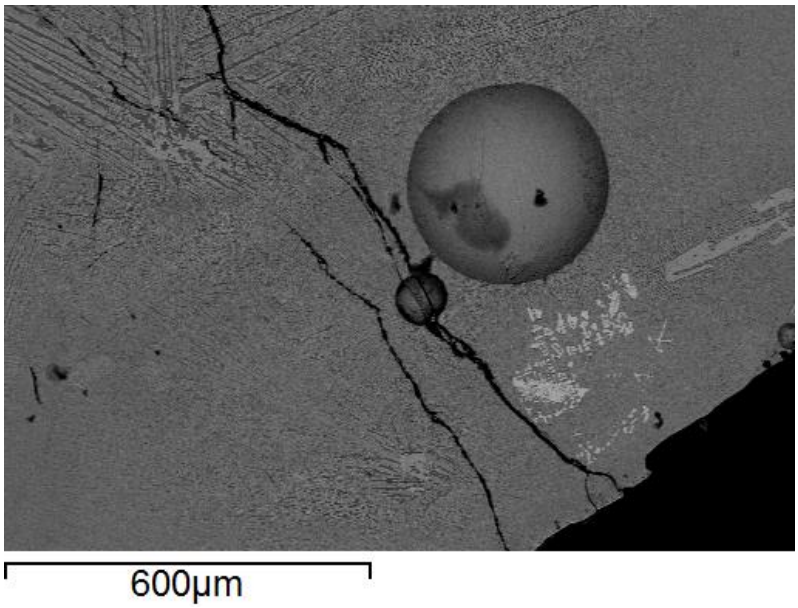

Figure 7.23: SEM-BSE image of secondary magnetite crystals in the Mkulusi #7 slags (7SE5)

Besides the formation of the crystals, it is shown in Table 7.26 that three of the five samples are supposedly impure crystals of magnetite with about 84 wt% FeO and 10 wt% alumina. This is not surprising, because some of the magnetite crystals are zoned (Figure 7.24). The other two samples (2SE2, 7SE5) are relatively pure with about 95 wt% FeO. Besides FeO and Al_2O_3, the magnetite crystals also contain some MgO, SiO_2, TiO_2, and MnO (see Table 7.26).

Table 7.26: SEM-EDS chemical composition of magnetite crystals from Ntuha and Mkulusi sites

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	TiO_2	MnO	FeO	Total
1	2SE1	0.1	12.8	1.6	0.9	1.6	83.4	100.8
2	2SE2	0.3	1.1	0.3	0.2	2.7	95.6	100.2
3	2SE3	0.3	9.1	0.4	0.5	1.4	88.3	100.3
4	1SE3	0.3	8.3	1.4	10.2	0.0	80.0	100.1
5	7SE5	0.3	4.3	0.4	1.0	0.1	94.4	100.5

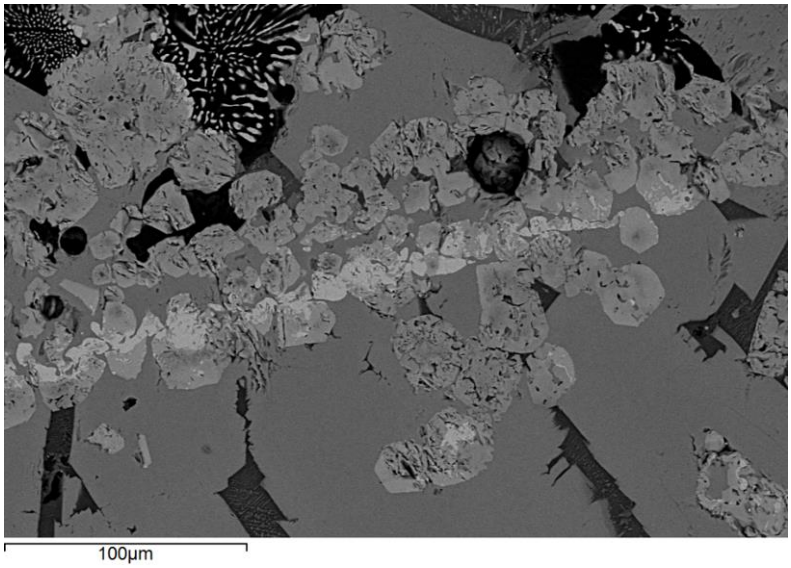

Figure 7.24: SEM-BSE image of zoned magnetite crystals (core rich in alumina) in the Ntuha slags (2SE1)

7.3.3.6 Tap lines

The slags from Ntuha site had no typical tap lines, while some of the slags from Mkulusi site #1 and Mkulusi site #7 exhibited clear magnetite tap lines (Figure 7.25). These tap lines represent separate tapping episodes, and were formed when the surface of slag flowing outside the furnace oxidized due to contact with the ambient air. This evidence perfectly accords with the relatively small and thin crystals of the other phases in the slags from these sites, and by extension, it attests that the smelters at the Mkulusi sites tapped slag outside the furnace. With this evidence, it can be argued that the technologies practised at the two (Ntuha and Mkulusi) areas were not similar as previously thought (Mapunda 1991: 7, 2001: 108).

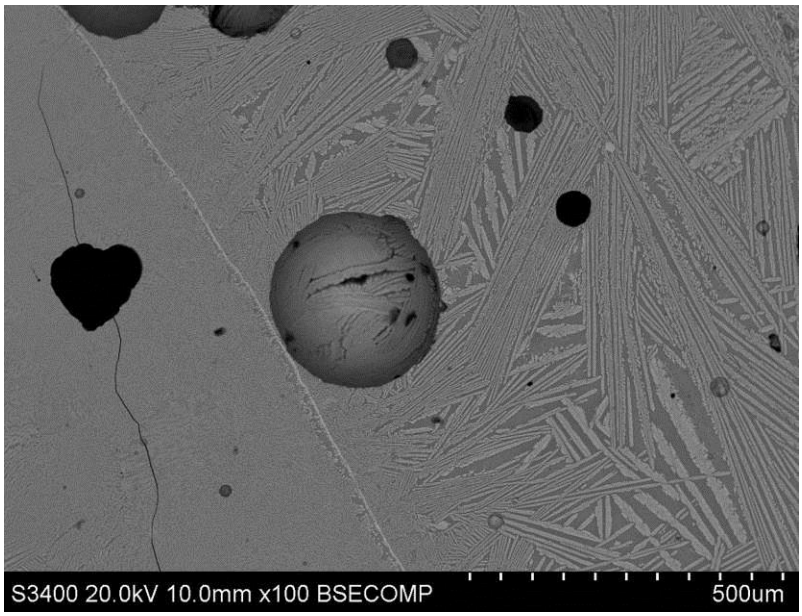

Figure 7.25: SEM-BSE image of a tap line from Mkulusi site #1 and #7 (7SE1)

7.3.3.7 Haematite crystals

None of the Mkulusi slags had haematite, but two samples (2SE3 and SSE5) from the Ntuha site showed up some oxidized layers of haematite (Figure 7.26). From the image, one notices a clear arrangement of iron oxides in the sequence: haematite-magnetite-wüstite. In order for this arrangement to develop so clearly required enough time and prolonged temperatures in oxidizing conditions. If this is true, it can be hypothesized that this happened in the furnace either in front of the hot tuyères or else when the furnace was dismantled for bloom collection. Whichever the case, it is unlikely that this formation could have happened outside the furnace, because of the thick nature of the crystals.

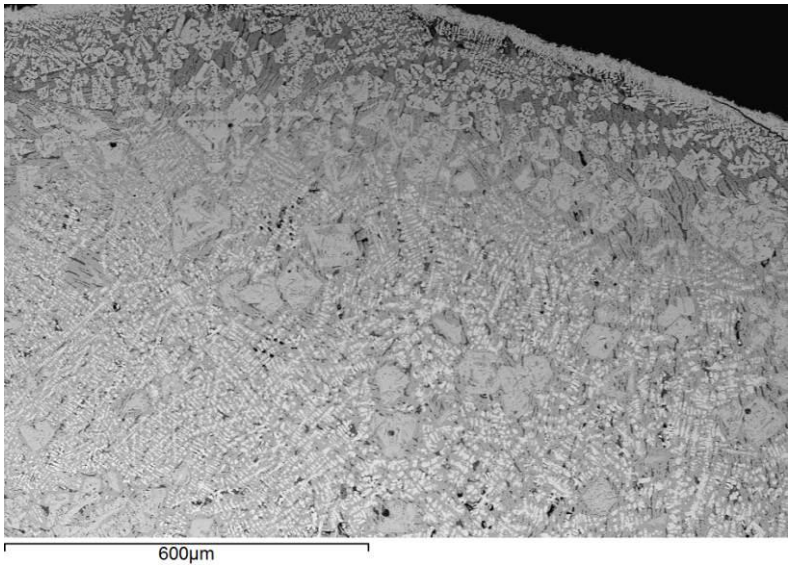

Figure 7.26: SEM-BSE image of arrangement of iron oxides (top haematite, middle magnetite, and bottom wüstite) in the slags from Ntuha site (SSE5)

7.3.3.8 Iron metal droplets

In addition to the apparent difference in the size and nature of the other crystals between the slags from the two (Ntuha and Mkulusi) areas, evidence of iron droplets also sets them apart. No iron droplets were observed in the Ntuha slags, but they were a prominent feature of the Mkulusi slags (Figure 7.27). Apart from exhibiting this difference between the two areas, the droplet/spherical shape of the metal inclusions, as well as the absence of wüstite or any free iron oxides in the slags from the Mkulusi area, is a strong indication of the more reducing conditions in the furnace and the better skills and experience of the smelters at these sites. If the strongly reducing conditions were maintained throughout the smelts, it should not be surprising that the majority of the metal from the ore and slags was reduced. Also, if the fuel to ore ratio was 2:1 or more, they may have produced high carbon steel. On average, the EPMA chemical composition of the droplets (Table 7.27) indicates that high carbon steel with about 1.7 wt% carbon and 97.8 wt% iron were perhaps produced in this area. Other alloyants of the droplet steel of Mkulusi were silicon (about 0.06 wt%), phosphorous (0.16 wt%),

aluminium (0.02 wt%), copper (0.06 wt%), nickel (0.11 wt%) and manganese (about 0.01 wt%). Although one of the samples (7SE1) contained cast iron droplets with 3.8 wt% carbon and 95.6 wt% iron, it is clear that the smelters systematically aimed at producing high carbon steel.

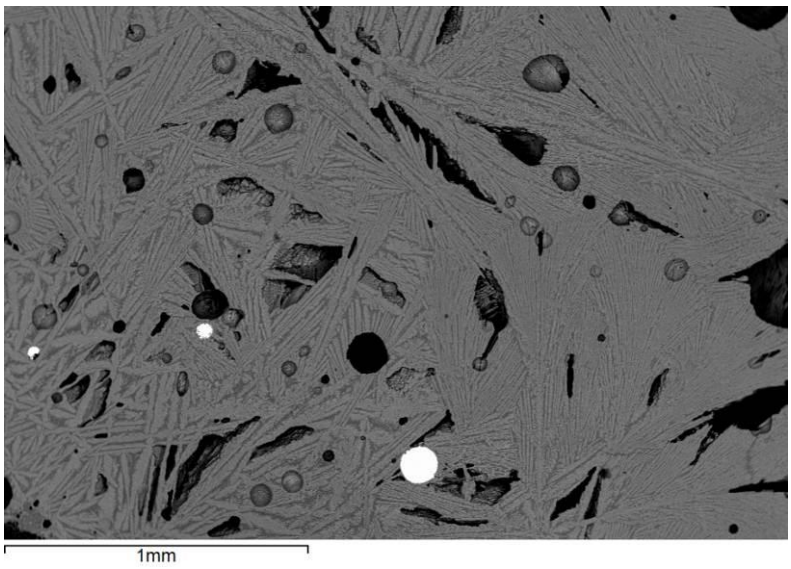

Figure 7.27: SEM-BSE image of the slag metal droplets inclusions from Mkulusi sites (1SE5)

Table 7.27: EPMA composition of the metal droplets from the Mkulusi smelting (SE) sites. Note the results are the average of several spectra (see Appendix 7.16) and are normalised to 100 wt%

S/No.	Sample/ Element	Si	P	Al	Cu	Ni	Co	Mn	C	Fe	Total
1	1SE1	0.01	0.24	0.01	0.02	0.06	0.08	0.01	1.12	98.45	99.87
2	1SE2	0.12	0.26	0.03	0.03	0.10	0.14	0.00	1.76	97.55	99.73
3	1SE3	0.08	0.06	0.03	0.14	0.17	0.12	0.00	0.87	98.53	100.30
4	7SE1	0.06	0.36	0.02	0.09	0.07	0.00	0.00	3.78	95.60	99.43
5	7SE2	0.06	0.04	0.03	0.06	0.03	0.01	0.03	1.21	98.51	99.31
6	7SE4	0.02	0.02	0.02	0.03	0.20	0.04	0.03	1.31	98.32	97.36

7.3.3.9 Leucite crystals

No leucite ($KAlSi_2O_6$) crystals were observed in the Mkulusi slags, but one of the Ntuha slags did contain leucite (Figure 7.28).

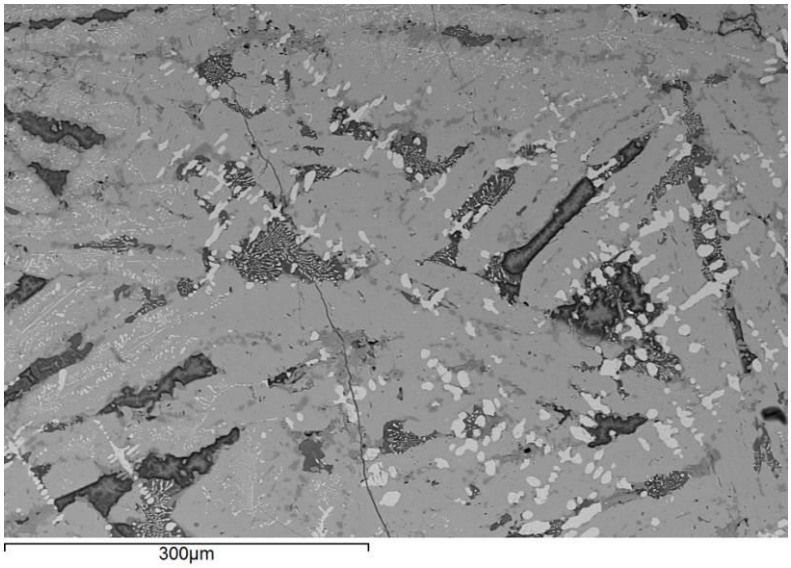

Figure 7.28: SEM-BSE image of the leucite crystals (black) from Ntuha site

7.3.3.10 Porosity and quartz crystals

The slags from the two areas were all porous, and some of the slags contained quartz particles. The quartz particles from the Ntuha sample are unreacted (Figure 7.29), but the slags from the Mkulusi area are clearly reacted or cracked (Figure 7.30). Unless they were intentionally added into the furnaces a practise of which I have no ethnographic data to support, it is possible that they were accidentally incorporated into the melt or slag. If this is true, then it might be correct to argue that during cooling process those quartz grains in the Ntuha sample did not crack because the melt cooled slowly, but the quartz in the Mkulusi cracked because the melt or slag cooled rapidly.

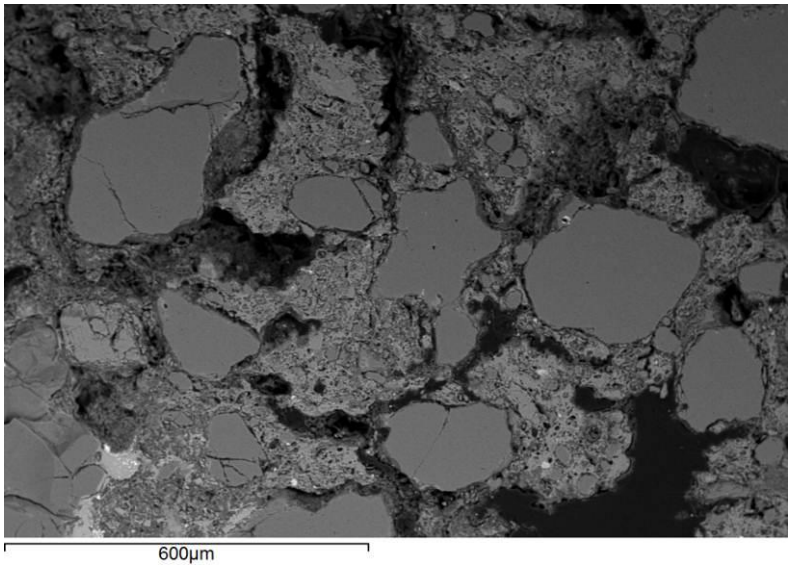

Figure 7.29: SEM-BSE image of the unreacted quartz particles from Ntuha site

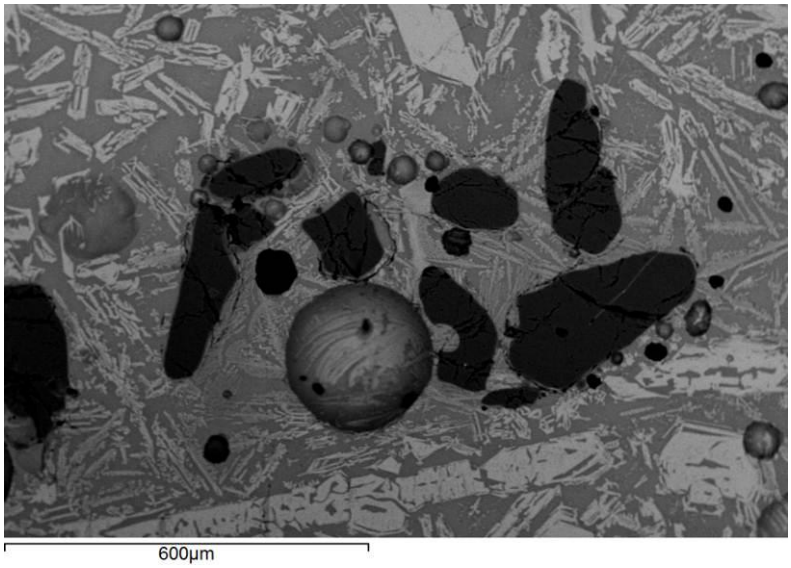

Figure 7.30: SEM-BSE image of the reacted, cracked quartz particles from the Mkulusi sites

7.3.3.11 Other crystals

There were two (1SE3 and 1SE5) other phases present in the slags of Mkulusi site #1, which based on their chemical compositions, the first appears to be an ulvite spinel with about 65 wt% TiO_2 and 32 wt% FeO on average, and the second could be an ilmenite rock fragment with about 50 wt% each TiO_2 and FeO. Given the low concentration of

TiO_2 in the bulk composition, it is unlikely these were part of the smelted ore. Instead they could be rock fragments that were accidentally incorporated into the slags.

7.4 Discussion of the Aims of the Chapter

The aims of this chapter were presented earlier in Chapter 2 (see Previous Archaeological Knowledge in Mbinga). The five aims included: (1) to find out the nature of the technical ceramics, (2) to examine the archaeological evidence for draught mechanism for the smelting *matendi* furnaces, (3) to verify whether or not later iron smelting furnaces had slag-pit provisions (e.g. Mapunda 1991: 69, 2001: 108), (4) to examine the efficiency of the metal production process, and (5) to suggest the nature of the smelted metal products from Lituhi and Kigonsera wards. Here these aims are briefly discussed in light of the new macroscopic and microscopic data gathered from this region.

First, the nature of the technical ceramics used for the construction of smelting furnaces and manufacturing of the tuyères and pottery in this area will be discussed. The technical ceramics at the Ntuha and Mkulusi sites were made from different clay sources. This was not unexpected, because each of these was subsequently subjected to different temperature intensities during the metal production processes (see Freestone and Tite 1986; Childs 1989b). For example, the crumbly and less refractory (possible) platform ceramics at the Ntuha site were exposed to relatively very low temperatures as opposed to the furnaces, tuyères, or pottery, which all were made with relatively high refractory clay. Also, and for the same reasons, the clay used in the production of the tuyères, pottery, and furnace walls of the Mkulusi sites were carefully selected from different sources. Because different clay sources produced ceramics with different refractory qualities, it can be argued that for the sake of a successful smelting campaign the smelters selected the clays based on their refractory quality. For example, at the

Mkulusi area the pottery and tuyères are more refractory than the furnace walls, although the tuyères were more dimensionally stable to heat shocks than the pottery. The tuyères have relatively more silica or quartz inclusions as illustrated above that pushes them towards the silica rich region of the Al_2O_3-SiO_2-FeO system. To sum up, the practise of the smelters in selecting the refractory ceramics alone shows how critical the ceramics were for the success of the metallurgical process (e.g. Freestone 1989: 156), which in turn reflects the skills they had (e.g. Freestone and Tite 1986: 36).

Second, the evidence for draught mechanisms of the smelting *matendi* furnaces of this region will be discussed. No flared tuyères have yet been recovered from the Ntuha (IiJc-4) site, which makes it uncertain whether or not a forced draft mechanism was used at this site. Mapunda (1991, 2001) has proposed that bellows could have been used, but the presence of two large stones at the site, which he argues were used for protecting bellowers from heat, could instead have primarily been there for the sake of ritual purposes (Pole 2010: 55 calls them guarding stones). Unless smelting campaigns in this area took place in the rainy season (although this is unlikely to have been the case), another anomaly to the proposed forced draft operation is the assumed charging platform. The platform could have been necessary for charging tall smelting furnaces of approximately 1.5 m high. The evidence of this height and the (supposedly) nine tuyère ports (Mapunda 1991) can be used to suggest a natural draft operation at the site (see van der Merwe and Avery 1987: 149).

On the other hand, the presence of flared tuyère ends at both Mkulusi site #1 and 7 is a strong indication that the iron smelters in the area used bellows to supply air into the furnace for the reduction process. The flared ends, which served as receptacles of the bellows, have been used elsewhere in Ufipa to associate the type of draught mechanisms for the smelting furnaces in the area (Mapunda 2010). If this interpretation is correct,

then it is possible to surmise that both the smelters from western (Kapinga 1990) and eastern Umatengo practised a forced draft furnace operation, but those at the Ntuha site may have operated their furnaces by a natural draft mechanism. The forced draft at the Mkulusi area employed multiple tuyères (at least three) in one port, and one furnace may have been operated by a pair of bellows (see Kapinga 1990).

The third question is whether or not recent iron smelting furnaces had slag-pit provisions (e.g. Mapunda 1991: 69, 2001: 108). Based on the relatively thick primary crystals of fayalite, wüstite, and magnetite as well as the absence of tap lines in the slags from the Ntuha site, it can be argued that the Ntuha smelting furnaces had slag-pit provisions at the bottom, where the growth of these large crystals took place during a slow cooling process. On the other hand, the presence of thin, skeletal, and elongated fayalite crystals in the Mkulusi slags indicates that here the slag cooled quickly outside of the smelting furnaces, which is verified by the tap line evidence for the slag tapping practise. Although Mapunda (1991, 2001) suggests that the ancient Ntuha and recent Matengo iron smelting practises were perhaps similar, the new evidence points to the possibility that the technologies of the areas were significantly different, which could easily be understood given their temporal and spatial disparities.

Fourth, the efficiency of the reduction process of the two areas will be discussed. Based on the dominance of primary wüstite crystals and the high free iron oxides in the slags of the Ntuha site, the Ntuha reduction process could be viewed as relatively less efficient than the Mkulusi process, where virtually no wüstite was left in the slags. Elsewhere on the continent, the lack of wüstite in the slags has been used to suggest highly efficient processes (e.g. Killick 1991: 64; Ige and Rehren 2003: 18; Miller and Killick 2004: 31; Iles and Martinón-Torres 2009: 2323). This microstructural evidence of the difference between the two areas is further strengthened by the bulk composition

data, with about 67 wt% FeO in the Ntuha area and 43 wt% FeO in the Mkulusi area on average. As well as this difference, factors such as the nature of the smelted ore, fuel to ore ratio, and effect of air supply can be considered as affecting the iron lost to the slag. For example, unless some sandy quartz is added into the furnace to facilitate formation of slag (e.g. Craddock *et al*. 2007: 10), smelting very rich ores with less than enough gangue material to form slag would unfortunately require some of the iron oxides sacrificed to form running slag (Morton and Wingrove 1972: 480). As such, if rich magnetite ores were smelted at the Ntuha site (Kapinga 1990), slags with high levels of wüstite should be expected, assuming that other factors were kept constant. In addition, the loss of significant amounts of iron oxides into the Ntuha slags could have been tolerated to save fuel rather than the supposedly plentiful magnetite iron ores (Kapinga 1990). Lastly, it is possible that the smelting temperatures might have been low, perhaps due to insufficient air supply into the furnace or low fuel to ore ratio, meaning that the CO/CO_2 ratio was lower than would be expected to reduce most of the iron in the ore or slag (see Morton and Wingrove 1969: 1557).

Conversely, the apparent metal reduction efficiency at the Mkulusi area was perhaps achieved at the cost of a relatively high fuel to ore ratio. Unfortunately, I have no archaeobotanical data to investigate the damage this fuel consumption inflicted on local forests (although oral evidence asserts that there were many natural forests and so it was possibly not as costly or damaging as it is today). In addition, the apparent use of multiple tuyères for air supply effected high metal yields and decreased loss of FeO in the slags at the Mkulusi area (e.g. Tylecote *et al*. 1971: 360; Chirikure 2006: 149). As noted earlier, the use of multiple tuyères in one port for a forced draft operation is unconventional, because "the only sure criterion of a natural draft seems to be the use of multiple tuyères in each port" writes Killick (1991: 63). Besides the supposedly high

fuel to ore ratio and effective air supply, labour (e.g. for gathering medicinal ingredients, ore, fuel energy, preparing furnaces and tuyères, and for pumping the bellows), experience, and time might have played a great role to achieve this end. These other aspects are less measurable but it does not mean they were unimportant.

Finally, the possible nature of the smelted metal products from the *matendi* furnaces of the two (Ntuha and Mkulusi) areas will be discussed. The apparent dominance of free iron oxides (especially wüstite) and the possible use of low fuel to ore ratio at the Ntuha site could have resulted in the production of soft iron metal, with low carbon (perhaps <0.02 wt% C) (see Tylecote *et al*. 1971: 352). We know that typical 'bloomery' slags contain large amounts of wüstite (Bachmann 1982: 15; Childs 1996: 291), and that its final product was a soft iron bloom (Bachmann 1982: 17). The iron smelters of this area may have preferred this soft metal, because it is easy to work. On the other hand, it is argued that the absence of wüstite in slags indicates possible production of steel, and certainly not soft iron (e.g. Ige and Rehren 2003: 20; Killick 2004a: 108). In addition, the high fuel to ore ratio increases metal yield, and accordingly increases carbon concentration in the metal (e.g. Tylecote *et al*. 1971: 352). Based on these two factors, it can be suggested that the smelters at the Mkulusi area produced steel. This position is confirmed by the presence of metal droplets in the slags indicative of highly reducing conditions of the furnaces. Metal droplet inclusions in slags have been used elsewhere in Sweden to predict cast iron production (see Tholander 1989: 38), but the EPMA compositional data of the droplets presented here suggests that high carbon steel with about 1.7 wt% carbon was produced at the Mkulusi area. The question of whether or not the steel droplets represent the final product is a difficult one, but not impossible to address. Killick and Gordon (1989) have published two principal mechanisms of iron (and steel) production, namely, primary reduction of iron (and steel) directly from the

ore, and the secondary reduction of the initially dissolved iron from the slag. If the Mkulusi smelting furnaces produced the direct high carbon steel through the so-called secondary iron reduction mechanism, where all of the iron oxide is initially dissolved in the slag from which they must be recovered (van der Merwe and Avery 1982: 153; Killick and Gordon 1989: 123), then there is no doubt that the droplets were remnants of drops which did not coalesce with the large lump of steel. Moreover, the fact that the slags were selected randomly but all contained such droplets (5 to 14 droplets per surface) is a strong indication for systematic and intentional production of steel in this area.

7.5 Summary

Both iron smelters in ancient and recent Umatengo carefully selected different clays for the construction and manufacturing of different technical ceramics, and in general, their selection was guided by the refractory quality of the clays, among other things. Although it has been assumed that the ancient and recent iron production processes in Umatengo were similar (Mapunda and Burg 1991; Mapunda 1991, 2001), I have now new archaeometallurgical data to argue that they were actually quite different especially in terms of air supply mechanism (natural versus forced draft mechanism), liquid slag drainage and handling methods (slag-pit versus slag tapping techniques), reduction efficiency (worse versus better smelters' operating skills), and that the iron smelters at Ntuha produced iron, but those smelters at the Mkulusi area systematically produced high carbon steel.

8. Iron Production in Rural Iringa

8.1 Preamble

This chapter focuses on spatial and temporal variation in iron production techniques in Rural Iringa district of the Iringa region (Figure 8.1). The land is referred to as Uhehe (land of the Hehe), because the indigenous majority are Hehe, a Bantu speaking tribe (LOT 2009: 22; Sutton 1969, 1971). This chapter is divided into four sections. The first and the second focus on presentation and interpretation of new macroscopic and microscopic data respectively. The third discusses the aims of the chapter in relation to the new data, and the last one provides a synthesis of the results by pin-pointing the major spatial and temporal characteristics of iron technology in the region.

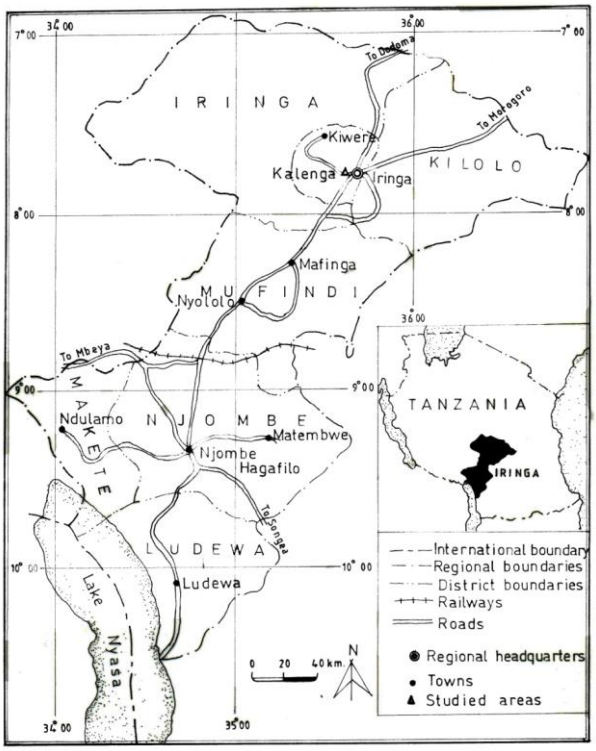

Figure 8.1: Map of Iringa region showing the location of Kalenga ward in Rural Iringa

8.2 Presentation and Interpretation of Macroscopic Data

8.2.1 Sites: Location, Size, Preservation, and Context of the Material

8.2.1.1 Location

The fieldwork research in rural Iringa district was conducted in Kalenga administrative division located about 15 km west of Iringa municipal centre. A total of 5 sites have been discovered from Ngongwa, Lukwambe, and Magubike villages (Figure 8.2; see also Appendix 8.1). With the exclusion of Magubike site #1, which has been radiocarbon dated to *cal.* 1320 and 1620 AD (dates were provided by Pamela Willoughby), the rest are yet to be radiocarbon dated, although they are likely to be more recent than the former. The sites are located between about 7^{o} 45.350' and 7^{o} 46.850' latitudes, and about 35^{o} 28.100' and 35^{o} 37.370' longitudes, at altitude 1544 m (on average) above mean sea level, and they are about 528 m (on average) from nearby water sources. If compared to the smelting sites from Mbinga located about 150 m from a water source, it becomes immediately noticeable that the Kalenga sites were located relatively far from water sources.

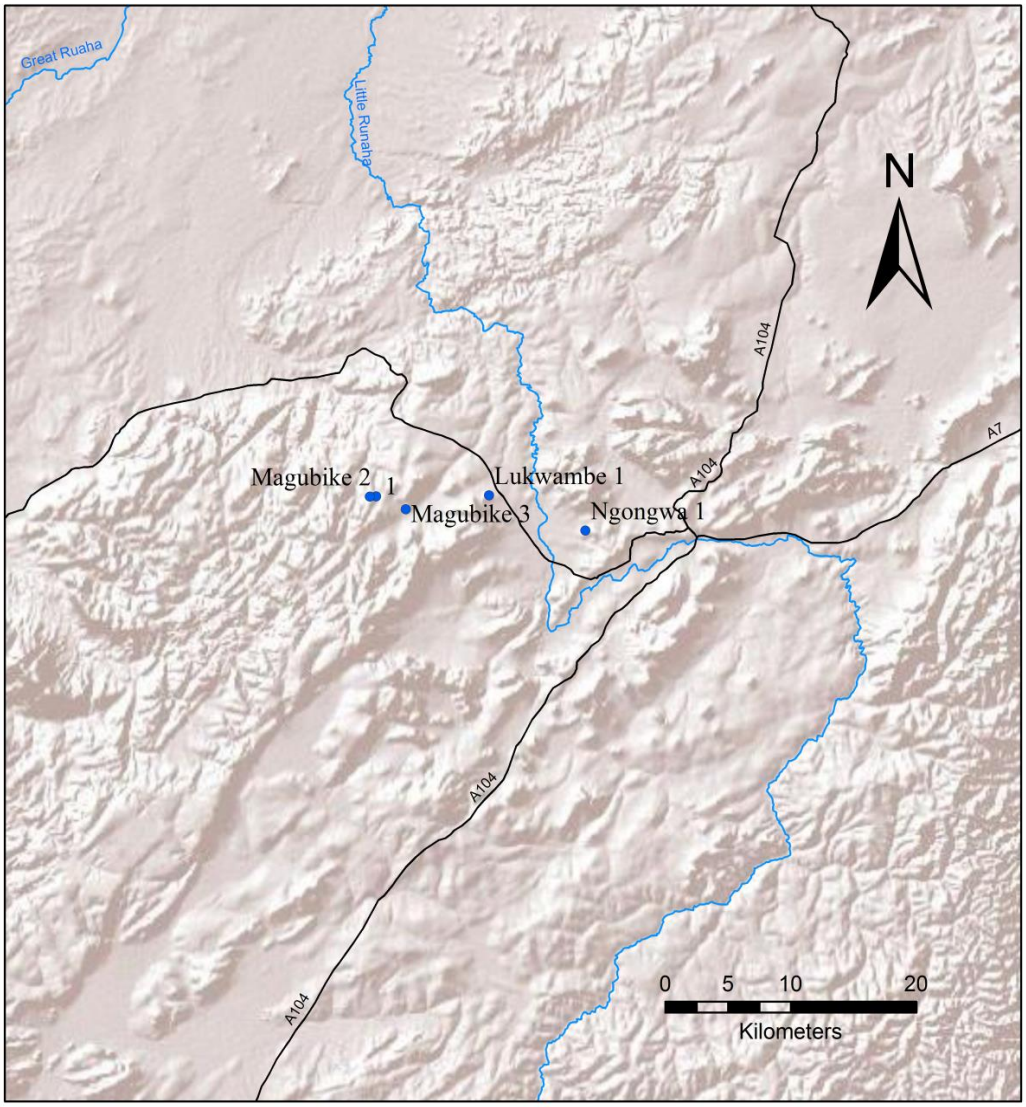

Figure 8.2: Map of the Kalenga ward showing the location of the studied villages and the distribution of the sites

8.2.1.2 Area size

The smelting sites have an area size of 246 m^2, on average. If compared to the smelting sites of Mbozi, with an area size of 156 m^2, it becomes clear that the latter are smaller than the former. One explanation is that the Kalenga sites are comprised of relatively numerous furnace bases (8-15) with lumps of intact slag. The other is that the smelting sites of Kalenga are systematically featured with supposedly working place(s) (WP) (Figure 8.3), where smelting furnaces were initially erected and then dismantled

supposedly for bloom collection. The furnace remains (clay rolls), tuyères, and slags were cleared off the WP for another smelt and were dumped all-round the WP where they accumulated into a large smelting debris concentration. It is also unclear whether the WP, measuring about 0.5-3 m deep and 24-29 m^2 area, could have served as clay sources for the furnace clay rolls manufacturing as well. Whichever was the case, it suffices to note that the inclusion of the WP as part of a particular site area, in addition to other widespread smelting debris, accounts for the relatively large area sizes of the Kalenga sites. There was no WP at Magubike site #1, apparently because it was fully buried before excavation.

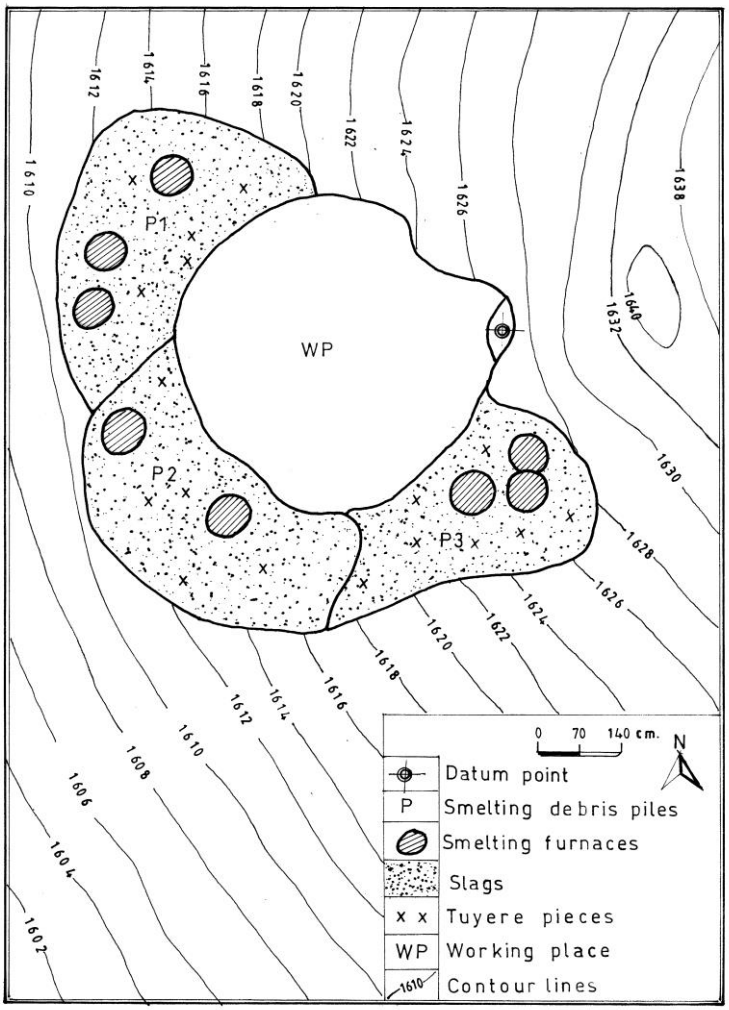

Figure 8.3: Working Place (WP) at Magubike site #2

8.2.1.3 Preservation

The smelting activities were situated in the mountains with the ground full of granite and pebble stones. Because of this, farmers have not cultivated or disturbed the smelting sites, leaving them well preserved, with all the material in their primary contexts.

8.2.1.4 Context of the Material

The materials for this chapter were surface collections as well as excavated archaeometallurgical remains. The surface material, especially the flared tuyères, was extracted whenever necessary from respective smelting debris heaps. The WP of the Ngongwa site #1 was excavated (Figure 8.4), in order to (1) test its subsurface distribution of the metallurgical remains, and (2) collect clay samples for chemical analysis. The latter aimed at testing whether the WP were a source of clay for the manufacturing of the technical ceramics, especially the furnace rolls. The excavation retrieved 2457 slags weighing 39 kg, 53 fragments of tuyères weighing 2 kg, 70 complete furnace clay rolls weighing 19 kg, 9 potsherds weighing 250 g, and 67 charcoal samples weighing 500 g. Another site, the materials of which were retrieved from excavation, is Magubike site #1 (or referred to as HwJf-2 by Pamela Willoughby). This site was excavated by Pamela Willoughby and colleagues (University of Alberta) interested in the Stone Age culture of the region. The excavated 'Iron Age' materials were made available to me (Table 8.1), and in addition, 247 slags equivalent to about 3 kg, and 31 pottery samples weighing 300 g were surface collections. So, the material collected included furnace clay rolls, tuyères, slags, pottery, and test clay samples.

Figure 8.4: WP of the Ngongwa #1 site showing the excavated Unit 2 (3x5 m^2)

Table 8.1: Excavated material from Unit 1 at Magubike (HwJf-2) smelting site #1

S/No.	Level (cm)	Slags #	Slags mass in g	Tuyères #	Tuyères mass in g	Metal objects #	Metal objects mass in g
1	A (0-5)	49	370	1	24	-	-
2	B (5-10)	302	2125	5	130	3	9
3	C (10-15)	-	-	-	-	1	9
4	D (15-20)	173	1040	-	-	1	4
5	E (20-40)	39	180	2	23	-	-
6	F (40-45)	10	60	-	-	-	-
7	**Sum**	**573**	**3775**	**8**	**177**	**5**	**22**
8	LSA Levels						
9	MSA Levels						

8.2.2 Furnace Attributes

No complete still-standing smelting furnaces were discovered, but it has been possible to encounter remnants of smelting furnaces measuring up to 10 cm high, and made of (wet) clay rolls measuring about 12-15 cm long and 5 cm thick (Figure 8.5). Comparatively, the Kalenga furnaces are relatively smaller than the Kigonsera furnaces (previous chapter), because they measure 46 cm for the external base diameters (EBD), 36 cm for the internal base diameters (IBD), and about 5 cm for the base wall thickness (BWT) (Table 8.2) while the Kigonsera furnaces measured 85 cm, 67 cm, and 9 cm for the EBD, IBD, and BWT respectively. Uniquely, the Kalenga furnace remnants each has a big lump of intact (flow) slag (Figure 8.6), and some of the remnants in the general smelting debris overlap each other (Figure 8.7). The former features suggest that they perhaps had slag-pit provision, and the latter indicates that the smelting furnaces were perhaps dismantled for iron collection before they were dumped with the other debris. Because of the (possible) shift of the furnace bases, it is impossible to measure the slag-pit dimensions with precision. Similarly, it has been difficult to reconstruct the actual height of the collapsed furnaces (see also Craddock *et al*. 2007: 5), but the presence of lots of (other) furnace clay rolls suggests that on top of the 10 cm height of the furnace bases, there must have been additional height. Oral evidence suggested that the smelting furnaces were about knee-high, but I am not entirely sure of the reliability of the oral data, because the Kalenga sites (excluding Magubike site #1) are not dated. Alternatively, based on the IBD of about 36 cm, it can be argued, the total height could have been at least 72 cm (see Davison and Mosley 1988; Schmidt 1997a). Davison and Mosley (1988: 75) have convincingly argued that the height of smelting furnaces must have been at least twice their diameters. It is unlikely that a thickness of 5 cm of the Kalenga furnace walls could have supported relatively tall heights, say, of at least 150

cm (Kigonsera furnaces height) without collapsing. Whichever the case, it suffices to learn that the Kalenga iron smelting furnaces were (short) shaft furnaces.

Figure 8.5: Furnace clay rolls of the (Ngongwa) smelting furnaces of the Kalenga division

Table 8.2: Dimensions of the iron smelting (SE) furnace base remnants from Kalenga sites. Note that EBD stands for external base diameter, IBD for internal base diameter, and BWT for base wall thickness

S/No.	Site	EBD (cm)	IBD (cm)	BWT (cm)
1	Ngongwa SE1	52	40	6
2	Ngongwa SE1	50	40	5
3	Ngongwa SE1	49	39	5
4	Lukwambe SE1	45	37	5
5	Lukwambe SE1	43.8	35	5
6	Lukwambe SE1	47	39	5
7	Magubike SE2	42	32	5
8	Magubike SE2	41	31	5
9	Magubike SE2	44	34	5
10	Magubike SE3	44	34	5
11	Magubike SE3	46	36	5
12	Magubike SE3	47	37	5
13	**Average**	**46**	**36**	**5**
14	**SD**	**3**	**3**	**0**

Figure 8.6: Smelting furnace bases from Kalenga filled in with lump of intact flow slags

Figure 8.7: Overlapping (Ngongwa) smelting furnace bases from Kalenga

8.2.3 Tuyère Ports and Tuyeres

8.2.3.1 Tuyère ports per furnace and tuyères per port

The remnants of the furnaces described above do not show tuyère slits, and I can posit that the tuyère ports were located more than 10 cm above the remnants, assuming that the lump of intact slag was part of the slag drained down into the slag-pit beneath the furnace. The absence of visible tuyère slits makes it difficult to explicitly tell the number of tuyère ports per furnace. Tentatively, based on the relatively small diameter of the Kalenga furnaces, I can think of two or three tuyère slits per furnace, and that each one housed one tuyère.

8.2.3.2 Tuyère attributes

The presence of flared proximal ends of the tuyères (Figure 8.8) strongly suggests that air supply was by a forced draft mechanism (see also Mapunda 2010). On average, the tuyères measured about 5 cm external diameter (ED), 3 cm internal diameter (ID), and 1 cm thickness (Table 8.3). Based on these dimensions, the Kalenga tuyères are relatively smaller than the Kigonsera tuyères, with 7 cm ED, 4 cm ID, and 2 cm thickness. Arguably, this would not be unexpected, because the smelting furnaces of Kigonsera were relatively larger than the Kalenga furnaces. What could have made a significant difference was the respective rate and speed of pumping the bellows (e.g. Klapwijk 1986a; Friede and Steel 1986a), of which I have no evidence. Based on the SD figures (see Table 8.3), it is possible that the smelters throughout Kalenga had standard techniques of manufacturing the tuyères. Finally, the tuyères of this region are relatively short, 9-16 cm, and weigh about 100-500 g, but the length may be less replicable, because they were incomplete tuyères.

Figure 8.8: Evidence of flared proximal ends of the tuyères from Kalenga region

Table 8.3: Macroscopic attributes of tuyères from Kalenga region. Note ED=external diameter, ID=internal diameter, SE=smelting, and SD=standard deviation

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Segment	Remarks
1	Ngongwa SE1	6	3.4	1.3	Proximal	Flared
2	Ngongwa SE1	5.3	2.9	1.2	Distal	Slag-coated
3	Ngongwa SE1	5.3	2.7	1.3	Body	
4	Ngongwa SE1	5.5	2.5	1.5	Proximal	Flared
5	Lukwambe SE1	5.2	3.4	0.9	Body	
6	Lukwambe SE1	5.9	2.7	1.6	Proximal	Flared
7	Lukwambe SE1	5.8	3.6	1.1	Proximal	Flared
8	Lukwambe SE1	5.8	3.4	1.2	Proximal	Flared
9	Magubike SE1	5.2	2.6	1.3	Distal	Slag-coated
10	Magubike SE1	5.8	3	1.4	Proximal	Flared
11	Magubike SE1	5.6	2.8	1.3	Body	
12	Magubike SE1	5.9	3.7	1.1	Proximal	Flared
13	Magubike SE2	4.5	2.1	1.2	Distal	Slag-coated
14	Magubike SE2	5	2.8	1.1	Body	
15	Magubike SE2	5.6	3.6	1	Proximal	Flared
16	Magubike SE2	5.7	3.5	1.1	Proximal	Flared
17	Magubike SE3	5.5	3.3	1.1	Proximal	Flared
18	Magubike SE3	5.2	2.8	1.2	Proximal	Flared
19	Magubike SE3	5	2.6	1.2	Distal	Slag-coated
20	Magubike SE3	5	3	1	Body	
21	**Average**	**5**	**3**	**1**		
22	**SD**	**0.4**	**0.4**	**0.2**		

8.2.4 Slag Attributes

The slags from Kalenga can be divided into three main morphological categories, namely, cake-like slags, droplet slags, and amorphous slags. The cake-like slags are further sub-divided into two groups: those slag lumps intact with the furnace remnants, and the typical cake-like slags. On average, the former are heavier and larger than the latter (Table 8.4). The difference in weight and size can be used to suggest that the typical cake-like slags lay underneath the furnace remnants, at the bottom of the furnaces. Similarly, the relative small size of the typical cake-like slags indicates that the slag-pit tapered downwards and apparently measured at least 15 cm deep.

Table 8.4: Macroscopic attributes of the smelting (SE) cake-like slags from Kalenga division. Note none of the cake-like slags were recovered from Magubike site #1, and FB=furnace base

S/No.	Site	Mass (Kg)	Length (cm)	Width (cm)	Thickness (cm)	Remarks
1	Ngongwa SE1	6	39	39	10	furnace base
2	Ngongwa SE1	25	40	39	11	furnace base
3	Ngongwa SE1	0.9	13	12	8.7	
4	Ngongwa SE1	0.6	4	3	2.5	
5	Lukwambe SE1	4	34	33	6	furnace base
6	Lukwambe SE1	2	36	35	11	furnace base
7	Lukwambe SE1	0.3	8	6	4	
8	Lukwambe SE1	0.4	8	6	5	
9	Magubike SE2	1.9	30	30	9.5	furnace base
10	Magubike SE2	2.2	32	31	11	furnace base
11	Magubike SE2	0.4	8	5	4.5	
12	Magubike SE2	0.3	9	5	4.5	
13	Magubike SE3	5.4	33	33	9	furnace base
14	Magubike SE3	3	35	35	9	furnace base
15	Magubike SE3	0.3	8	6	5	
16	Magubike SE3	0.5	10	9	7	
17	**Average (FB)**	**6**	**35**	**34**	**10**	
18	**Average (2)**	**0.5**	**9**	**7**	**5**	
19	**SD (FB)**	**8**	**3**	**3**	**2**	
20	**SD (2)**	**0.2**	**3**	**3**	**2**	

The droplets are relatively smaller and roundish (Figure 8.9; Table 8.5). These are formed when slag drips down through, say, grass medium into the slag-pit provision at the bottom of the furnace. Elsewhere in the Kagera region, northwest Tanzania, large quantities of droplets have reasonably been used as diagnostic markers for the slag-pit furnaces of the Haya (see Schmidt and Childs 1985: 56). Although droplet slags are also characteristic of smithing sites, the latter are distinctively hollow and relatively more oxidised and magnetic than the former (see Miller and Killick 2004: 26; Lyaya 2007). As well as the lumps of intact slags with the Kalenga remnants, the presence of the droplet slags in substantial quantity in Kalenga makes it more probable that the smelting furnaces had slag-pit provision.

Figure 8.9: Droplet slags from the (Ngongwa) Kalenga area

Table 8.5: Macroscopic attributes of the smelting (SE) droplet slags from the Kalenga division. Note that none of the droplet slags were retrieved from Magubike site #1

S/No.	Site	Mass (g)	Length (mm)	Width (mm)	Thickness (mm)
1	Ngongwa SE1	6	7	6.5	6
2	Ngongwa SE1	0.5	5	5	4.4
3	Ngongwa SE1	0.5	7	6.8	6
4	Lukwambe SE1	0.4	5	5	4.5
5	Lukwambe SE1	0.5	4	3.9	3.8
6	Lukwambe SE1	0.9	7	7	6.9
7	Magubike SE2	1	9	8.7	8
8	Magubike SE2	1.2	7	6.8	6
9	Magubike SE2	0.7	7	7	6
10	Magubike SE3	2	8	8	7
11	Magubike SE3	0.2	3	3	2.6
12	Magubike SE3	6	6	6	5.6
13	**Average**	**2**	**6**	**6**	**6**
14	**SD**	**2**	**2**	**2**	**2**

Lastly, the amorphous slags are relatively rough, oxidised, and magnetic on bar and pencil magnets (Figure 8.10). They are greatly variable in weight and size (Table 8.6). The roughness of these slags matches nicely with the slag-pit provision hypothesis for the Kalenga furnaces (see also mineralogical data).

Figure 8.10: Amorphous smelting slags of the (Ngongwa) Kalenga area

Table 8.6: Macroscopic attributes of the smelting amorphous slags from Kalenga division

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)	Remarks
1	Ngongwa SE1	106	5	3.7	1.9	
2	Ngongwa SE1	500	5.4	2.7	1.2	
3	Ngongwa SE1	700	4.3	4	3.5	
4	Lukwambe SE1	217	5	3	2.7	
5	Lukwambe SE1	2800	9.5	5.6	2.9	
6	Lukwambe SE1	1800	6.8	4.2	2.9	
7	Magubike SE1	55	5.1	3.5	2.3	Level A
8	Magubike SE1	53	5.1	3.6	2.6	Level B
9	Magubike SE1	105	7.1	6.1	2.8	Level D
10	Magubike SE1	20	3.3	2.2	1.5	Level E
11	Magubike SE1	30	4	2.9	1.4	Level F
12	Magubike SE2	442	7	6	3.7	
13	Magubike SE2	6400	6.7	5	4	
14	Magubike SE2	1400	5	3	3	
15	Magubike SE3	1390	4	3.7	2.3	
16	Magubike SE3	1960	3.4	2.3	1.7	
17	Magubike SE3	160	4	3	2	
18	**Average**	**1067**	**5**	**4**	**2**	
19	**SD**	**1610**	**2**	**1**	**1**	

8.2.5 Pottery

With the exception of Magubike site #2, potsherds were encountered and collected from all the Kalenga sites. Nine potsherds were retrieved from Ngongwa site #1 WP and weighed about 220 g, five potsherds weighing about 200 g were surface collections from Lukwambe site #1, 31 potsherds weighing about 310 g were retrieved from the excavation of Magubike site #1 (by Pamela Willoughby), and seven potsherds equivalent to about 290 g were surface collections from Magubike 3 site. Unfortunately, all the potsherds were undecorated bodies. This as well as the fact that these sites (except Magubike site #1) are not dated, has made it difficult to relate them stylistically to other pottery traditions in the country, but for the purpose of the current project, they are examined chemically to determine whether they were made of separate clays from the other technical ceramics.

In addition, I encountered one (ceramic) accessory at Magubike site #2 (Figure 8.11; see also the profile in Appendix 8.2). It is somewhat like a pot, with a small (dolly) hole. I think it was a container of some sort. Careful observation suggests that the top was relatively more burnt than the bottom; it is black with tiny (almost negligible) spells of slags. It has been difficult to guess with precision its technological function at this site, but an attempt is made. In the hole we have seen nothing except a few tiny roots, vegetal matters, and some black humus soils. Although the locals thought it was used to light fire, it appears too soft for that function. Alternatively, it was used as a ritual or medicinal container, in place of the popular perforated pots (e.g. Schmidt 1997a; 2006; Mapunda 1995b; 2010) placed at the bottom of the smelting furnace.

Figure 8.11: Ritual or medicinal container from Magubike #2 site: left is top and right is bottom

8.3 Presentation and Interpretation of Microscopic Data

8.3.1 Technical Ceramics Chemical Data

The chemical analysis of the technical ceramics aimed at (1) investigating whether the supposed WP was a source of clays for the furnace rolls, (2) finding out whether the iron producers were clay-selective for the construction and manufacturing of the different technical ceramics and (3) examining the refractory quality of the technical ceramics in relation to the intended technical purposes.

First, on average, there is more silica concentration in the test briquettes (WP clay) than in the furnace walls (clay rolls) of the Ngongwa site #1, in part because the former were collected from the centre of the WP where more quartz sands (silica) had gradually accumulated owing to water erosion. The increase in silica concentration (and soda) diluted and lowered the concentration of alumina, potash, lime, magnesia, and titania, although the remaining were unaffected (see Table 8.7). Disregarding the sampling problem, and considering the similarity of two sets of ceramics in their trace oxide

concentration (Table 8.8), it seems likely that the furnace clay rolls were possibly made from the WP clays.

Second, on average, there is more silica and less concentration of the other oxides in the tuyères than in the pottery of the Ngongwa site #1 (Table 8.7). This systematic difference extending to trace oxide concentration (see Table 8.8) suggests that the two sets of ceramics were perhaps made from different sources of clay.

Apart from Ngongwa, the iron smelters at Magubike site #2 might have used separate clay sources for the manufacturing of the furnace clay rolls and tuyères as well, because there is more concentration of silica, potash, and soda, and, less concentration of the other oxides in the tuyères than in the furnace clay rolls. This chemical distinction is observed by most of the trace oxides as well. For both sites, the smelters selected clays rich in silica for the tuyères, in order to improve the dimensional stability (see Freestone and Tite 1986).

Table 8.7: (P) XRF-EDS Major and minor element concentrations (in wt%) of technical ceramics from Kalenga smelting sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 8.3; FW=furnace wall, TB=test briquettes, PTR=pottery, and TYR=tuyère

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
Technical ceramics from Ngongwa site #1													
1	1FW1	0.64	1.29	20.56	68.67	0.01	3.98	1.40	0.47	0.01	0.09	2.89	97.44
2	1FW2	0.59	1.29	20.73	68.51	0.01	3.97	1.42	0.47	0.01	0.09	2.91	97.51
3	1FW3	0.66	1.42	19.96	68.28	0.01	3.90	2.21	0.48	0.01	0.10	2.99	97.60
4	1PTR1	0.73	0.89	20.85	67.66	0.01	3.12	1.31	0.53	0.01	0.05	4.85	97.70
5	1PTR2	0.73	0.88	21.37	67.00	0.01	2.69	1.40	0.56	0.01	0.11	5.24	97.64
6	1PTR3	0.77	0.86	21.19	67.52	0.01	2.66	1.37	0.55	0.01	0.05	5.01	97.36
7	1TB1	0.95	1.05	12.13	77.66	0.00	3.57	1.33	0.31	0.01	0.09	2.91	98.24
8	1TB2	0.99	1.08	12.75	76.63	0.00	3.82	1.40	0.31	0.01	0.08	2.94	98.04
9	1TB3	0.95	1.05	12.77	76.71	0.00	3.79	1.40	0.31	0.01	0.08	2.93	98.20
10	1TYR1	0.20	0.41	27.82	66.83	0.02	1.51	0.13	0.59	0.01	0.02	2.47	96.70
11	1TYR2	0.22	0.43	27.91	66.70	0.02	1.52	0.12	0.59	0.01	0.02	2.46	96.62
12	1TYR3	0.23	0.43	27.64	67.06	0.02	1.51	0.11	0.57	0.01	0.02	2.40	96.61
Technical ceramics from Magubike site #1													
13	1-2TYR1	0.96	1.48	15.72	71.37	0.00	3.02	2.75	0.48	0.01	0.08	4.13	98.14
14	1-2TYR2	0.85	1.82	17.03	69.17	0.01	3.03	2.81	0.54	0.01	0.08	4.65	98.59
15	1-4TYR3	0.85	1.07	17.42	70.77	0.01	3.37	1.61	0.49	0.01	0.05	4.35	98.43
Technical ceramics from Magubike site #2													
16	2FW1	0.15	0.56	28.01	60.05	0.04	4.88	0.42	0.88	0.01	0.12	4.89	98.60
17	2FW2	0.22	0.50	26.43	61.60	0.02	4.95	0.48	0.83	0.01	0.14	4.82	98.73
18	2FW3	0.15	0.59	28.76	60.03	0.04	4.75	0.47	0.87	0.01	0.14	4.20	98.15
19	2TYR1	0.24	0.60	24.05	63.37	0.01	5.48	0.99	0.78	0.01	0.16	4.32	99.35
20	2TYR2	0.22	0.56	25.16	62.92	0.02	5.45	0.59	0.85	0.01	0.17	4.04	98.92
21	2TYR3	0.20	0.32	21.68	67.81	0.02	5.91	0.17	0.66	0.01	0.06	3.15	99.41

Table 8.8: (P) XRF-EDS Trace element concentrations (in ppm) of technical ceramics from Kalenga smelting sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 8.4; FW=furnace wall, TB=test briquettes, PTR=pottery, and TYR=tuyère

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	Hf	WO_3	PbO	Th
Technical ceramics from Ngongwa site #1																		
1	1FW1	27	30	21	31	11	76	111	12	167	5	251	13	21	9	44	16	11
2	1FW2	32	31	22	33	12	77	111	11	172	5	241	12	17	8	42	17	11
3	1FW3	37	36	43	32	12	79	113	11	147	5	233	13	17	8	78	13	10
4	1TB1	39	32	12	25	7	56	96	10	229	3	213	9	18	10	95	16	10
5	1TB2	27	33	18	27	8	58	99	10	224	3	233	10	14	10	41	17	9
6	1TB3	29	34	19	27	8	58	100	11	224	2	230	9	13	9	46	17	9
7	1PTR1	44	25	23	28	12	45	117	9	62	3	286	6	17	5	98	14	8
8	1PTR2	54	26	24	27	13	44	120	10	68	3	274	6	48	4	80	23	8
9	1PTR3	49	24	21	28	13	46	117	10	67	3	287	7	26	5	77	16	8
10	1TYR1	28	8	24	32	14	51	20	12	178	26	116	13	21	8	128	17	19
11	1TYR2	25	8	24	31	14	51	20	12	180	25	120	12	17	9	128	18	18
12	1TYR3	27	9	23	34	14	51	20	11	181	26	115	13	20	9	163	16	19
Technical ceramics from Magubike site #1																		
13	1-2TYR1	45	27	72	38	9	51	232	12	123	2	307	9	19	6	129	12	10
14	1-2TYR2	48	36	65	44	10	54	239	13	120	2	312	9	21	7	100	12	10
15	1-4TYR3	38	18	129	29	10	48	213	10	145	3	272	6	10	8	87	14	10
Technical ceramics from Magubike site #2																		
16	2FW1	43	6	46	48	18	138	111	26	466	14	298	25	59	20	13	35	59
17	2FW2	50	7	47	41	17	137	104	26	460	14	293	26	59	19	24	29	54
18	2FW3	45	10	76	44	18	136	125	26	410	14	288	26	61	18	15	32	48
19	2TYR1	42	9	59	40	16	150	130	27	510	11	313	28	60	22	72	25	66
20	2TYR2	46	9	44	46	16	151	122	29	519	12	316	27	63	22	38	30	52
21	2TYR3	32	6	128	27	13	138	92	18	468	11	282	12	33	20	80	23	49

Third, Figure 8.12 indicates that the technical ceramics were virtually different in refractory qualities. The tuyères were more refractory (1700 ^{o}C) than pottery and furnace rolls (1600 ^{o}C), probably because they were subjected to relatively higher temperatures than the last two (see Freestone and Tite 1986; Hein *et al*. 2007). The furnace clay rolls and pottery were similar in terms of the refractory quality, but the former were dimensionally stronger than the latter, because they have slightly more silica concentration (see Tite *et al*. 2001: 319). It is noteworthy that all the ceramics are more stable than is required by the process, and the difference in temperature would have possibly not made a practical difference for the furnace, operating at 1200 ^{o}C to 1300 ^{o}C. Although it is shown that the test briquettes (TBs) were less refractory than the

furnace rolls, as explained above, the difference in silica could have been due to sampling problems of the briquette clay. It is difficult to understand where the smelters got the clays for the construction of the furnaces and why the WP apparently deepened so.

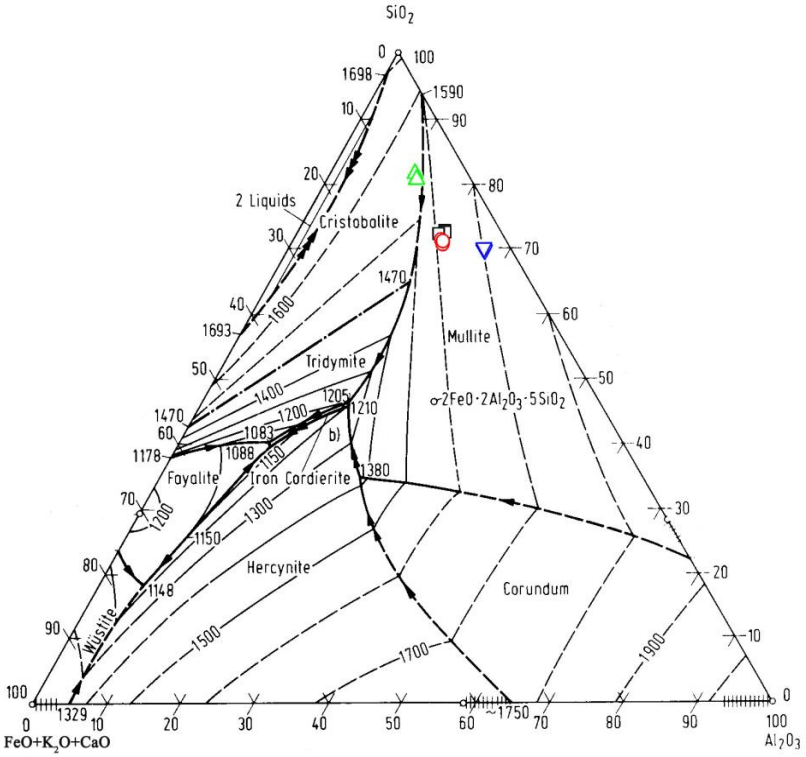

Figure 8.12: Al_2O_3-SiO_2-FeO phase diagram for the technical ceramics from Ngongwa site. The circles (red) are pottery, the upward triangles (green) are test briquettes, the squares (black) are furnace rolls, and the downward triangles (blue) are tuyères

Lastly, Figure 8.13 suggests that the tuyères of Magubike site #1 were relatively less refractory than tuyères from Magubike site #2. The tuyères and furnace clay rolls of Magubike site #2 were similar in terms of refractory quality, although the tuyères were more dimensionally stable than the furnace rolls, because quartz has relatively high fracture strength and thermal conductivity (e.g. Tite *et al*. 2001: 315). Therefore, the smelters, out of repeated experience, may have added quartz or selected quartz-rich clay to increase the thermal shock resistance of the tuyères.

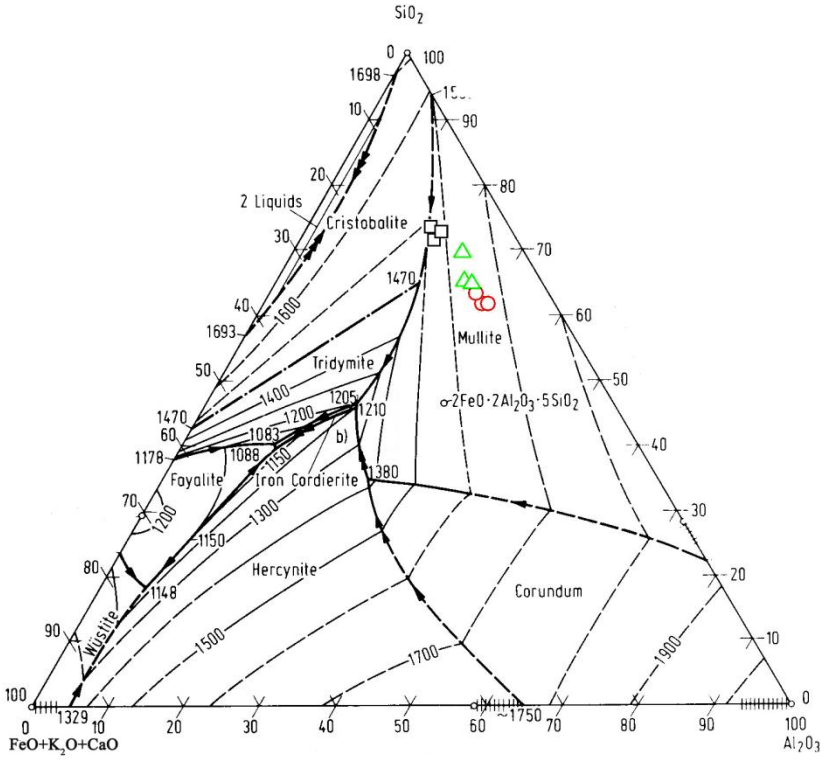

Figure 8.13: Al_2O_3-SiO_2-FeO phase diagram for the technical ceramics from Magubike site #1 and #2 sites. The circles (red) are furnace rolls, the upward triangles (green) are tuyères from Magubike site #2, and the squares (black) are tuyères from Magubike site #1

8.3.2 Slag Chemical Data

For the sake of clarity, the bulk area composition data of the slags from the three sites are presented and discussed together (Table 8.9). On average, the Ngongwa slags have relatively less concentration of iron oxide than in the Magubike site #1 and #2 (see Table 8.9) indicating differences in operational skills of the smelters at the sites. Magubike site #1 has lower FeO concentration than Magubike site #2, possibly because of the use of calcium-rich iron ores, which decreased the loss of iron into the slags (see Table 8.9).

In addition, on average, there is more silica, alumina, zirconia, and titania in the Ngongwa slags than in the Magubike site #1 and #2 samples. The differences in lime and zirconia indicates that the smelters at Magubike site #1 may have used or rather added $CaCO_3$ into the charge as a flux, and that the smelters of Ngongwa site #1 and

Magubike site #2 more probable smelted iron ores rich in zirconium. Disregarding metal inclusions and unreacted quartz grains (see Appendix 8.5), none of the three sites operated at Optimum zone 1, although Ngongwa site #1 iron smelters were closer to the most efficient zone (see Figure 8.14; Rehren *et al*. 2007: 212, 214) than those smelters from Magubike site #1 and #2 sites operating round Optimum zone 2.

Table 8.9: SEM-EDS major and minor oxide concentrations (in wt%) of the smelting slags from Kalenga sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 8.6

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	ZrO_2	Total
Smelting slags from Ngongwa site #1														
1	1SE5	0.7	0.3	5.4	25.4	0.2	2.2	1.7	1.0	0.2	0.2	58.5	4.4	100.6
2	1SE6	0.8	0.5	5.7	30.8	0.3	2.0	1.6	1.5	0.2	0.2	52.9	3.7	100.3
3	1SE7	0.4	0.4	4.6	23.0	0.1	2.0	1.6	1.2	0.2	0.3	60.8	5.8	100.6
4	1EA1	0.6	0.5	6.2	28.7	0.2	1.9	1.7	1.3	0.0	0.2	53.7	5.4	100.6
5	1SA1	0.5	0.3	6.1	25.3	0.1	2.4	1.4	1.2	0.1	0.1	58.4	4.2	100.5
Smelting slags from Magubike site #1														
6	1-1SE1	0.6	0.8	3.5	18.8	0.2	1.2	6.9	0.3	0.0	0.1	67.0	0.3	93.4
7	1-2SE2	1.0	2.0	6.0	27.2	1.0	2.5	23.8	0.1	0.0	0.1	36.1	0.2	94.7
8	1-2SE3	0.3	1.0	4.6	19.1	0.2	1.7	7.9	0.4	0.0	0.2	62.3	3.2	101.7
9	1-3SE4	0.5	1.0	2.8	12.6	0.1	0.7	8.9	0.1	0.1	0.1	72.7	0.2	98.01
10	1-4SE5	1.3	0.4	6.1	25.0	0.3	1.6	2.8	0.1	0.0	0.0	62.4	0.2	106.9
Smelting slags from Magubike site #2														
11	2SE1	0.1	0.2	4.3	27.2	0.2	2.4	1.7	0.4	0.1	0.2	59.2	3.6	100.0
12	2SE2	0.4	0.3	5.2	28.1	0.1	2.4	1.2	0.5	0.2	0.1	59.3	2.6	100.4
13	2SE3	0.1	0.4	4.3	26.7	0.0	2.0	1.0	0.3	0.2	0.2	62.7	2.7	100.4
14	2SE4	0.2	0.2	4.5	20.6	0.1	1.8	0.9	0.5	0.2	0.1	69.4	2.0	100.5
15	2SE5	0.2	0.3	4.2	20.5	0.1	1.7	0.8	0.4	0.2	0.2	69.7	2.2	100.4

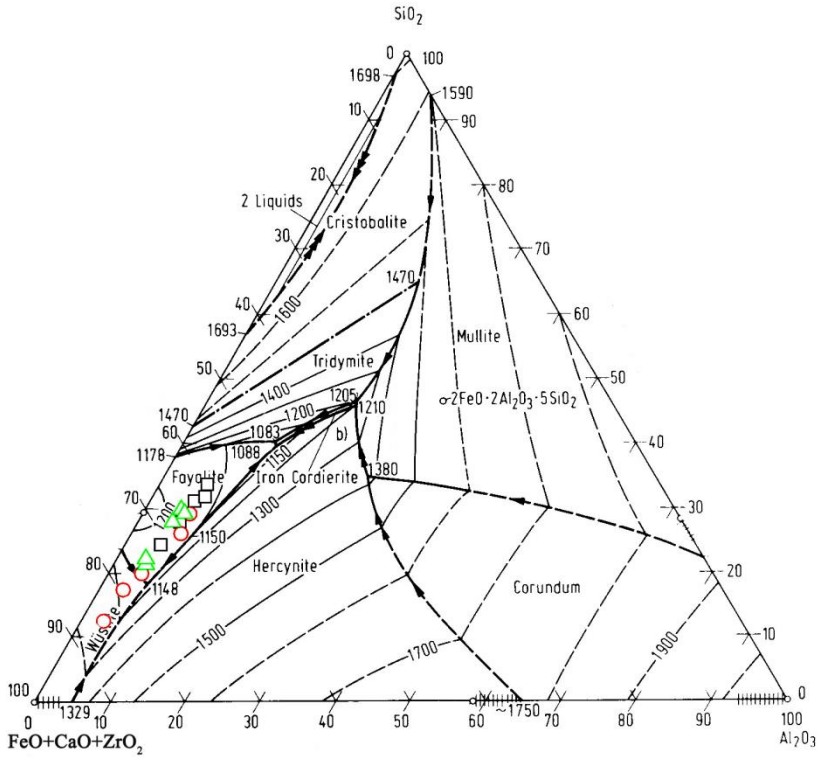

Figure 8.14: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting slags from Ngongwa (black squares), Magubike site #2 (green triangles), and Magubike site #1 (red circles)

The proposed difference in iron ores for the three sites is further supported by differences in the trace oxide concentration (Table 8.10). For example, there is more cobalt, nickel, copper, and strontium in the Magubike site #1 samples than in the Ngongwa site #1 and Magubike site #2 slags. In addition, Magubike site #1 slags contain less yttrium, molybdenum, barium, cerium, hafnium, and uranium oxides than Ngongwa site #1 and Magubike site #2 samples. The remaining trace oxides including zinc, niobium, cesium, tantalum, tungsten, lead, and thorium show no systematic difference across the three, but based on the systematic differences, it can be argued, ancient ironworkers at Magubike site #1 used a different ore, and that their successors, Ngongwa site #1 and Magubike site #2, switched over to a different one, apparently rich in zirconium.

Table 8.10: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting slags from Kalenga sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 8.7

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	SrO	Y	Nb_2O_5	Mo	Cs	Ba	Ce	Hf	Ta_2O_5	WO_3	PbO	Th	U
Smelting slags from Ngongwa site #1																		
1	1SE5	147	11	13	4	125	62	10	28	8	401	80	336	14	20	8	13	42
2	1SE6	130	10	13	24	127	67	10	27	8	384	228	317	14	18	7	12	31
3	1SE7	120	4	6	6	51	29	8	20	13	150	45	148	6	8	4	6	12
4	1EA1	133	10	13	16	150	99	11	35	8	346	292	476	19	16	7	12	37
5	1SA1	164	12	22	7	75	49	10	24	9	179	125	289	18	19	10	17	33
Smelting slags from Magubike site #1																		
6	1-1SE1	177	14	38	5	572	19	9	9	9	135	18	19	17	19	10	16	15
7	1-2SE2	95	20	45	5	1439	25	5	4	7	455	9	9	15	14	3	4	8
8	1-2SE3	170	14	26	5	390	31	9	23	9	123	17	244	23	21	10	16	31
9	1-3SE4	263	334	123	7	637	13	7	6	9	134	12	23	28	24	12	18	17
10	1-4SE5	157	21	45	5	243	12	7	6	8	146	11	15	18	17	9	14	14
Smelting slags from Magubike site #2																		
11	2SE1	150	11	15	5	250	109	12	32	8	188	110	411	16	21	11	2	99
12	2SE2	140	10	11	4	271	106	14	23	9	651	114	267	17	20	11	2	126
13	2SE3	150	11	12	5	232	102	13	20	9	558	102	286	14	19	11	2	127
14	2SE4	182	13	18	5	142	68	10	17	9	274	65	232	17	22	13	13	81
15	2SE5	180	13	15	5	149	69	12	19	9	274	80	214	18	24	13	12	78

8.3.3 Slag Mineralogical Data

Here I present and discuss the microstructures of the Kalenga smelting slags from the three sites (Table 8.11). For the purpose of comparing further the technological processes of the three areas, each of the phases is examined and discussed alone, starting with the fayalite through the quartz grains.

Table 8.11: Summary of the crystals of smelting slags from Kalenga sites

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Zirconia	Wustite	Magnetite	Fe particles	Leucite	Porosity	Quartz	Others
Smelting slags from Ngongwa site #1												
1	1SE5	√	-	√	-	√	-	√	-	√	-	-
2	1SE6	√	-	√	√	-	-	√	-	√	-	-
3	1SE7	√	-	√	√	√	-	√	-	√	-	√
4	1EA1	√	-	√	√	-	-	-	-	√	-	√
5	1SA1	√	-	√	√	√	-	√	√	√	-	-
Smelting slags from Magubike site #1												
6	1-1SE1	√	-	√	-	√	-	√	-	√	-	-
7	1-2SE2	√	-	√	-	√	√	√	√	√	√	-
8	1-2SE3	√	-	√	-	√	√	√	-	√	√	-
9	1-3SE4	√	-	√	-	√	-	√	-	√	-	-
10	1-4SE5	√	-	√	-	√	-	√	√	√	-	-
Smelting slags from Magubike site #2												
11	2SE1	√	-	√	√	√	-	√	√	√	-	-
12	2SE2	√	-	√	√	√	-	√	√	√	-	√
13	2SE3	√	-	√	√	√	-	√	√	√	-	-
14	2SE4	√	√	√	√	√	-	√	-	√	-	-
15	2SE5	√	√	√	√	√	-	√	√	√	-	-

8.3.3.1 Fayalite and monticellite crystals

Based on Table 8.12 all the smelting slags from Ngongwa #1 and Magubike #2 sites have pure fayalite ($2FeO.SiO_2$) crystals, because 2 mol of FeO combine with 1 mol of silica. The samples from Magubike site #1, excluding sample 1-4SE5, contained pure

monticellite ($FeO.CaO.SiO_2$) crystals, although some FeO are replaced with MgO concentration (see Table 14). The three oxides of the monticellite crystals combine to the ratio of 1:1:1 (see Bachmann 1982: 14).

Fayalite crystals in the slags are relatively short and thick (Figure 8.15) indicating that they cooled slowly perhaps in the furnace slag-pit. Although the monticellite crystals are more connected to each other than fayalite crystals, they are blocky as well (Figure 8.16). It is difficult to tell with precision the microstructural differences between the fayalite and monticellite without the aid of the chemical data. Because the ore smelted at Magubike site #1 was supposedly different from that smelted at Ngongwa site #1 and Magubike site #2, it is unsurprising that the resultant silicate crystals are so chemically different.

Besides FeO, CaO, and SiO_2, the crystals of Ngongwa site #1 and Magubike site #2 slags contain magnesia, alumina, manganese, zirconia, phosphate, potash, and soda.

Table 8.12: SEM-EDS chemical composition (in wt%) of fayalite and monticellite in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%, the full results in Appendix 8.8

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	FeO	ZrO_2	Total
Smelting slags from Ngongwa site #1												
1	1SE5	0.0	1.2	0.3	30.3	0.0	0.1	0.5	0.4	66.5	0.7	100
2	1SE6	0.1	1.8	0.1	30.3	0.0	0.0	0.2	0.4	66.9	0.2	100
3	1SE7	0.1	1.2	0.3	30.2	0.0	0.0	0.5	0.4	66.6	0.7	100
4	1EA1	0.0	1.5	0.1	30.6	0.1	0.1	0.3	0.3	67.2	0.2	100
5	1SA1	0.1	0.7	0.2	30.2	0.0	0.0	0.5	0.4	67.9	0.1	100
Smelting slags from Magubike site #1												
6	1-1SE1	0.1	1.3	0.7	32.7	0.7	0.4	22.6	0.0	41.8	0.1	100
7	1-2SE2	0.1	3.9	-0.1	34.1	0.4	0.0	33.5	0.1	28.2	0.1	100
8	1-2SE3	0.1	1.8	0.6	33.4	0.5	0.6	23.7	0.3	38.5	0.6	100
9	1-3SE4	0.8	0.5	5.4	34.5	0.7	2.2	31.2	0.0	24.9	0.1	100
10	1-4SE5	0.1	1.5	0.1	31.4	0.3	0.0	0.8	0.1	66.2	0.3	100
Smelting slags from Magubike site #2												
11	2SE1	0.0	0.8	0.3	30.7	0.4	0.0	0.5	0.1	66.9	0.3	100
12	2SE2	0.1	0.8	0.2	30.7	0.0	0.0	0.3	0.1	67.5	0.3	100
13	2SE3	0.1	0.8	0.4	30.6	0.1	0.1	0.4	0.2	66.6	0.6	100
14	2SE4	0.0	0.9	0.1	30.3	0.1	0.0	0.4	0.2	68.1	0.0	100
15	2SE5	0.0	0.9	0.1	30.4	0.0	0.1	0.4	0.2	67.5	0.3	100

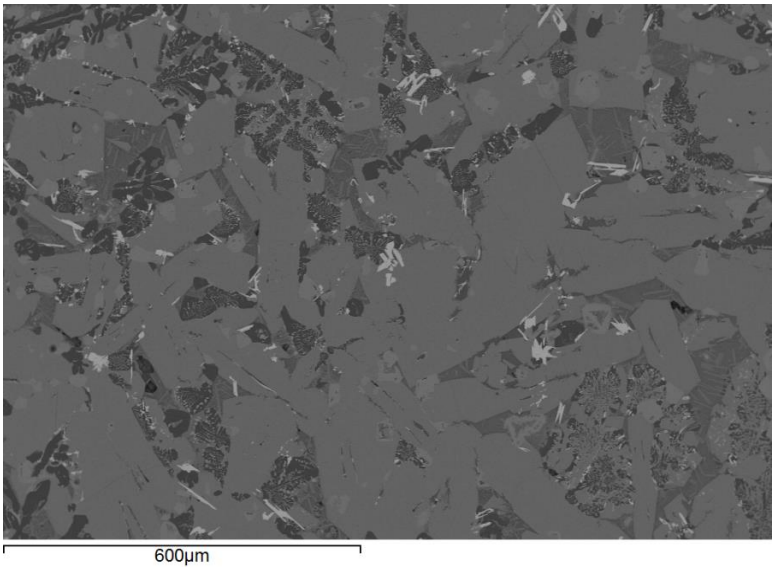

Figure 8.15: Blocky fayalite microstructures (light grey) of Kalenga smelting slags (sample 1SA1). Note white crystals (pointed) are zirconia, glass (dark grey), and porosity (black)

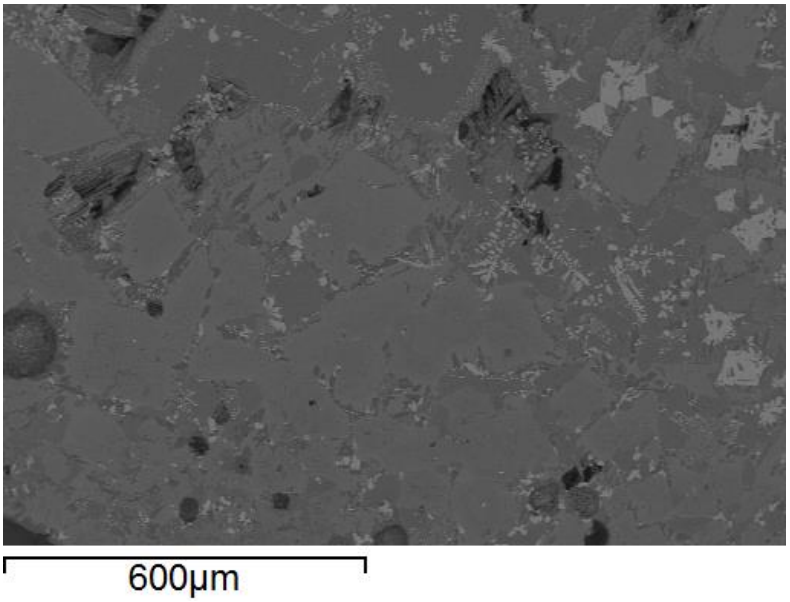

Figure 8.16: Blocky monticellite microstructures (light grey) of Kalenga smelting slags (sample 1-2SE2). Note angular (white) are magnetite crystals, glass (dark grey), and porosity (black)

8.3.3.2 Hercynite crystals

None of the Ngongwa and Magubike site #1 slags contained hercynite crystals, while 2 samples from Magubike site #2 had less dominant hercynite concentrated at the edges (see Table 8.11; Figure 8.17). The paucity of these crystals suggests that there was generally less alumina in the system. In terms of composition, they are pure hercynite crystals, and included silica, lime, titania, vanadia, and chromia.

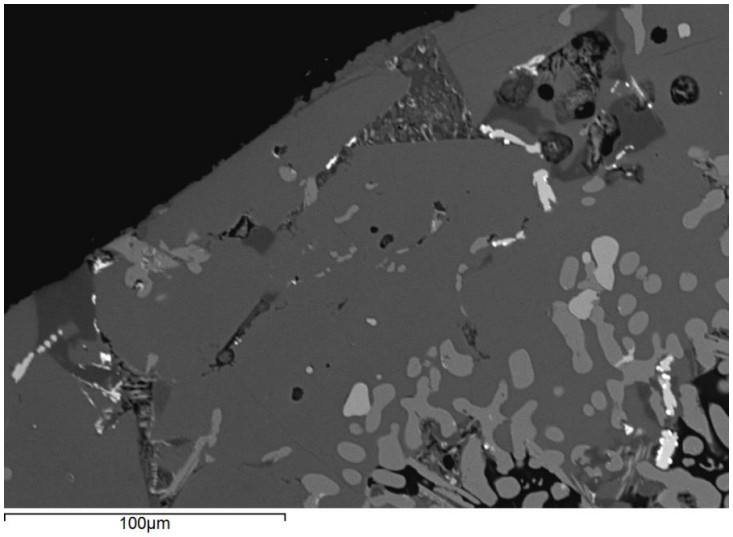

Figure 8.17: Hercynite crystals (dark grey) from Magubike site #2 slags (sample 2SE4). Note the iron particles (white), zirconia (bright white), fayalite (grey), glass (dark grey), and porosity (black)

8.3.3.3 Glass groundmass

There is generally low volume of glass in the slags, because the fayalite and monticellite crystals apparently cooled slowly with enough time to grow thick microstructures, leaving little medium for the groundmass (Figure 8.18). The main components of the glass of the Ngongwa and Magubike site #1 and #2 slags are FeO, SiO_2, and Al_2O_3, and CaO particularly for the slags from Magubike site #1 (Table 8.13). There is almost more concentration of the fuel ash indicators including soda, phosphate, and potash in the Ngongwa slags than in the Magubike site #1 and #2 slags. This subtle but systematic observation indicates that perhaps the smelters at the former site used relatively higher fuel to ore ratio than those at the latter sites, a possibility supported by the apparent production of relatively lean slags at the former (see Figure 8.14).

Other minor constituents of the glass phase are SO_3, TiO_2, ZrO_2, MoO_3, Ag_2O, In_2O_3, BaO, Ce_2O_3, and PtO_2.

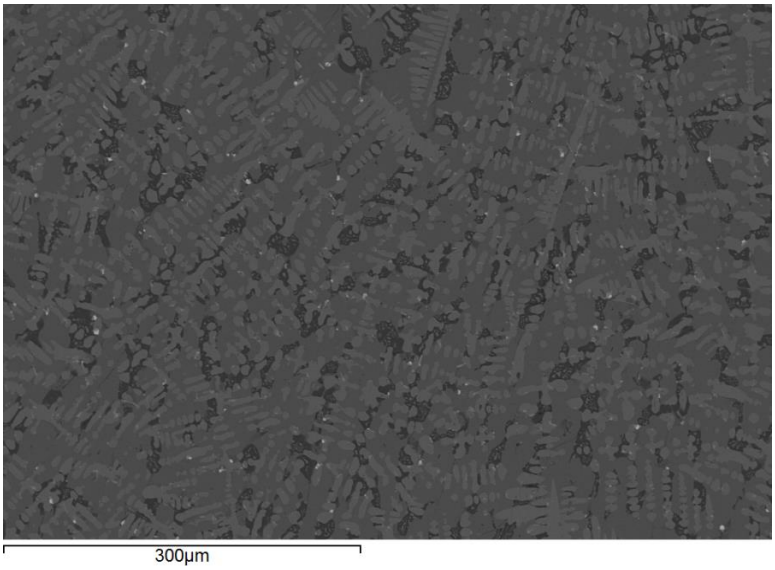

Figure 8.18: SEM-BSE image of (little) glass volume (black groundmass) in Kalenga slags (sample 2SE5). Note fayalite crystals (grey), wüstite (bright grey), zirconia (bright white), and glass (dark grey)

Table 8.13: SEM-EDS chemical composition (in wt%) of glass groundmass in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Na_2O	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	FeO	ZrO_2	MoO_3	Ag_2O	In_2O_3	BaO	Ce_2O_3	PtO_2	Total
Smelting slags from Ngongwa site #1																		
1	1SE5	2.0	15.8	41.6	0.8	0.2	9.3	8.0	0.8	17.6	1.7	0.2	0.1	0.7	0.7	0.2	0.1	100
2	1SE6	2.0	13.1	44.4	0.8	0.0	7.3	6.5	0.5	22.2	1.5	0.2	0.1	0.2	0.4	0.7	0.1	100
3	1SE7	1.6	14.5	41.5	1.1	0.2	10.1	7.9	0.7	18.2	2.4	0.3	0.1	0.9	0.7	0.2	0.1	100
4	1EA1	0.4	12.6	33.8	0.8	0.0	6.3	9.5	2.0	26.5	7.1	0.2	0.1	0.4	0.1	0.7	0.3	100
5	1SA1	4.6	12.2	37.1	2.2	1.0	2.0	12.9	0.1	22.1	2.7	0.4	0.5	0.2	1.0	1.3	0.2	100
Smelting slags from Magubike site #1																		
6	1-1SE1	1.6	12.2	39.9	0.9	0.9	6.5	10.9	1.4	22.1	2.8	-0.3	0.0	0.6	0.2	0.2	0.1	100
7	1-2SE2	1.2	8.6	39.6	0.3	0.2	0.4	37.6	0.0	12.2	-1.3	0.3	0.0	0.5	0.1	0.1	1.0	100
8	1-2SE3	1.7	15.1	43.7	1.4	0.2	10.4	7.4	0.7	14.3	3.7	0.1	0.0	0.8	0.5	0.1	0.1	100
9	1-3SE4	1.7	15.4	33.6	0.7	0.1	10.2	18.8	0.1	17.7	-0.7	0.1	0.1	0.9	0.4	0.2	0.6	100
10	1-4SE5	2.9	16.3	39.8	1.2	0.0	5.1	10.1	0.3	23.4	-0.5	0.0	0.0	0.5	0.3	0.1	0.8	100
Smelting slags from Magubike site #2																		
11	2SE1	0.3	9.1	32.9	0.6	0.6	6.1	7.4	0.7	32.4	8.4	0.3	1.1	-0.1	0.2	0.3	0.6	100
12	2SE2	0.7	15.9	39.0	0.6	0.3	10.2	6.2	0.4	20.9	2.6	0.3	1.2	0.2	1.1	0.4	0.0	100
13	2SE3	0.4	15.6	43.5	0.5	0.0	12.6	2.3	0.3	22.3	0.4	-0.1	0.2	0.4	1.0	0.3	0.3	100
14	2SE4	0.7	18.4	46.1	0.1	0.1	13.9	0.5	0.1	18.2	-0.3	0.2	0.0	0.9	0.8	0.1	0.4	100
15	2SE5	0.6	18.5	43.9	0.1	0.1	12.2	0.4	0.4	23.3	-0.4	0.1	-0.1	0.1	0.3	0.0	0.5	100

8.3.3.4 Zirconia crystals

These were absent in the slags from Magubike site #1, while all the smelting slags from Ngongwa site #1 and Magubike site #2 systematically contained zirconia crystals (Figure 8.19). The presence and absence of these crystals respectively depended on whether or not the smelters used zirconium-rich iron ores. Zirconia is relatively brighter (white) than iron particles, small particles, and usually pointed crystals. The small size of the crystals has made it difficult to examine with precision the chemical composition of all the particles on the SEM-EDS. Nonetheless, based on those precisely measured (samples EA1, and SA1), on average, they contain about 91 wt% ZrO_2, 4 wt% Re_2O_7, 3 wt% FeO, and 1 wt% HfO_2.

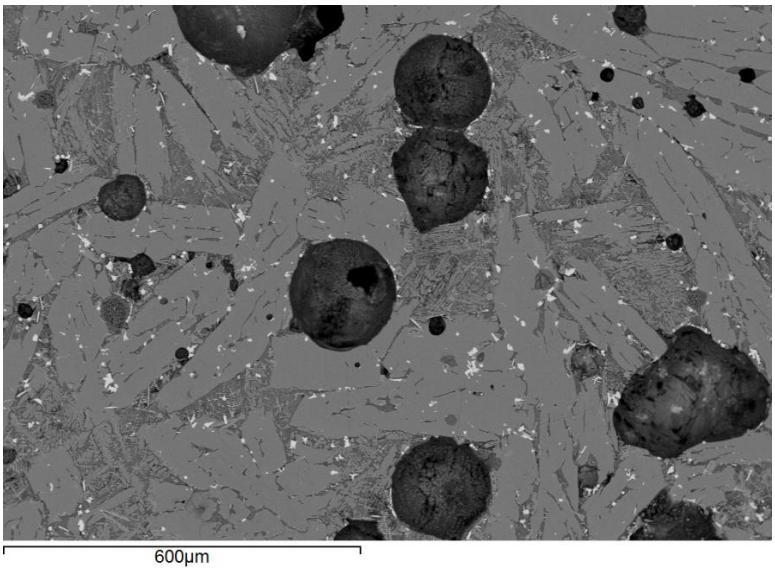

Figure 8.19: SEM-BSE image of zirconia crystals (brighter white) in the Kalenga slags (sample 1EA1). Note blocky fayalite crystals (grey), porosity (round black), and glass (dark matrix)

8.3.3.5 Wüstite crystals

There were only 3 slags out of 5 slags with wüstite crystals from Ngongwa site, but all the samples from Magubike site #1 and #2 had (primary) wüstite crystals (Figure 8.20). The presence and dominance of wüstite in the slags give an indication of how much iron

was wasted into the slags, and, to a certain extent, reflects on the effectiveness and skills of the smelters to control the operating parameters (e.g. Morton and Wingrove 1969, 1972). Like fayalite and monticellite crystals, the large size of the wüstite crystals suggests that they cooled slowly perhaps in the furnace slag-pit. Besides FeO (95-97 wt%), alumina, silica, titania, zirconia, magnesia, vanadia, chromia, and lime were present as minor constituents (Table 8.14).

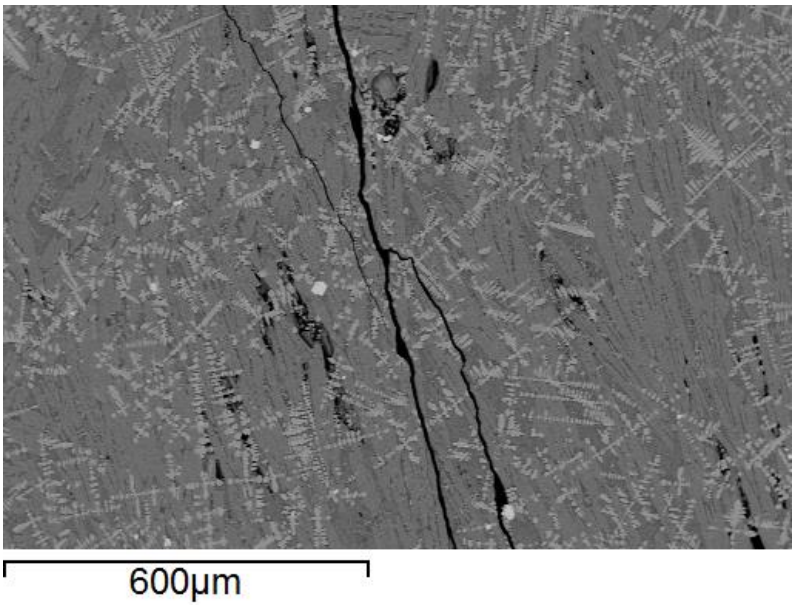

Figure 8.20: SEM-BSE image of wustite crystals (less bright white) dominant in the Kalenga slags (sample 2SE1). Note the iron particles (roundish and bright white), glass (dark grey), and fayalite (grey), and porosity and cracks (black).

Table 8.14: SEM-EDS chemical composition (in wt%) of wüstite in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	CaO	TiO_2	V_2O_5	Cr_2O_3	FeO	ZrO_2	Total
Smelting slags from Ngongwa site #1											
1	1SE5	0.2	0.6	0.9	0.2	1.6	0.3	0.0	95.5	0.6	100
2	1SE7	0.1	1.1	0.8	0.1	3.6	0.4	0.1	93.0	0.9	100
3	1SA1	0.0	0.4	0.7	0.1	0.8	0.0	0.0	97.4	0.5	100
Smelting slags from Magubike site #1											
4	1-1SE1	0.8	0.5	0.2	0.3	0.2	0.1	0.1	97.5	0.2	100
5	1-2SE2	0.5	0.7	0.1	0.5	0.2	0.0	0.1	97.9	0.2	100
6	1-2SE3	0.2	0.8	0.4	0.0	0.7	0.1	0.1	97.1	0.7	100
7	1-3SE4	1.5	0.6	0.2	0.3	0.0	0.1	0.1	97.0	0.2	100
8	1-4SE5	0.1	0.8	0.6	0.0	0.2	0.1	0.0	98.0	0.1	100
Smelting slags from Magubike site #2											
9	2SE1	0.1	0.8	0.7	0.0	1.0	0.8	0.7	95.3	0.6	100
10	2SE2	0.1	0.2	0.8	0.0	0.3	0.6	0.6	97.0	0.4	100
11	2SE3	0.0	0.6	0.8	0.1	0.5	1.0	0.8	96.0	0.2	100
12	2SE4	0.1	0.6	0.5	0.0	0.7	0.5	0.3	96.7	0.6	100
13	2SE5	0.0	0.3	0.4	0.0	0.5	0.4	0.2	97.6	0.5	100

8.3.3.6 Magnetite crystals

Two samples from Magubike site #1 had few magnetite crystals (Figure 8.21). The crystals appear to be a primary generation, because they are relatively thick equally suggesting that they had enough time to grow thick in a less oxidising condition. The presence of the primary high free iron oxide crystals in the slags strengthens the proposition that there were large losses of iron into the slags at this site. The magnetite crystals contained about 98 wt% FeO, 0.7 wt% MgO, 0.6 wt% Al_2O_3 and TiO_2, and 0.2 wt% SiO_2 and CaO.

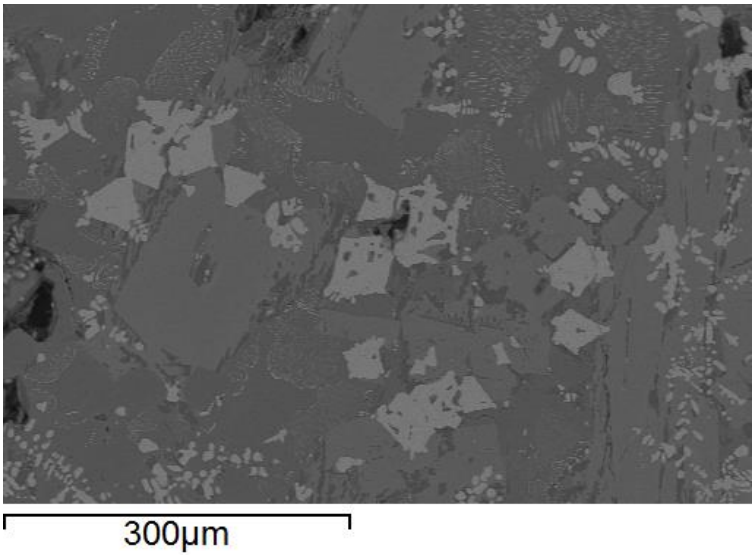

Figure 8.21: SEM-BSE image of primary magnetite crystals in Magubike site #2 slags (sample, 1-2SE2). Note blocky monticellite (grey), glass (dark grey), and porosity (black)

8.3.3.7 Iron metal particles

Almost all the slags had iron particles (see Table 8.11). They are frequently associated with wüstite crystals (Figure 8.22). It is possible that iron reduction and consolidation in this area followed the secondary reduction mechanism, where iron oxides such as wüstite were first dissolved in slag before they were eventually reduced into iron metal (e.g. van der Merwe and Avery 1982; Killick and Gordon 1989). The reduced iron metal particles agglomerated into a massive lump (e.g. van der Merwe and Avery 1982: 153). Based on this explanation, Figure 8.23 represents the already reduced metal particles that unfortunately did not agglomerate into the massive lump of iron metal, possibly because the smelting conditions were critically not optimal for this to happen. Both the loss of iron oxides and the metal particles in the slags indicate that the final iron yield was small per smelt, unless the conditions were later on improved.

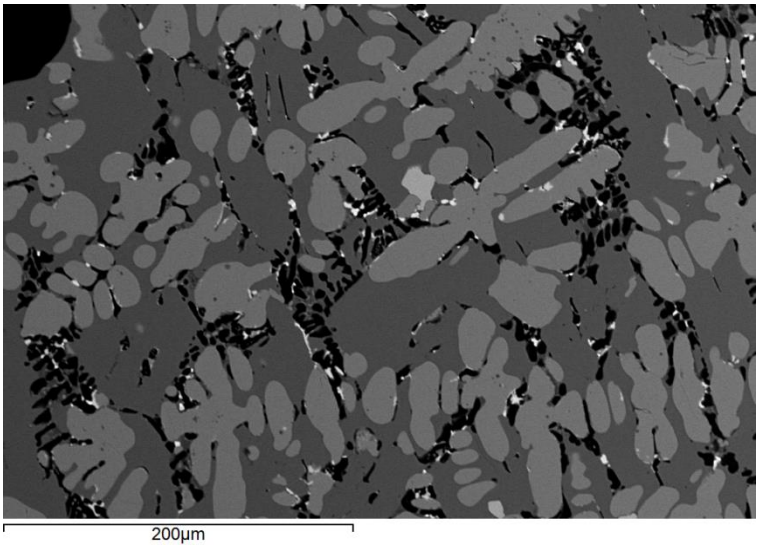

Figure 8.22: SEM-BSE image of the iron metal particles (white) developing from wüstite crystals (dark white) of the slags from Kalenga area (sample, 2SE4). Note blocky fayalite (grey), glass (dark grey), and porosity (black)

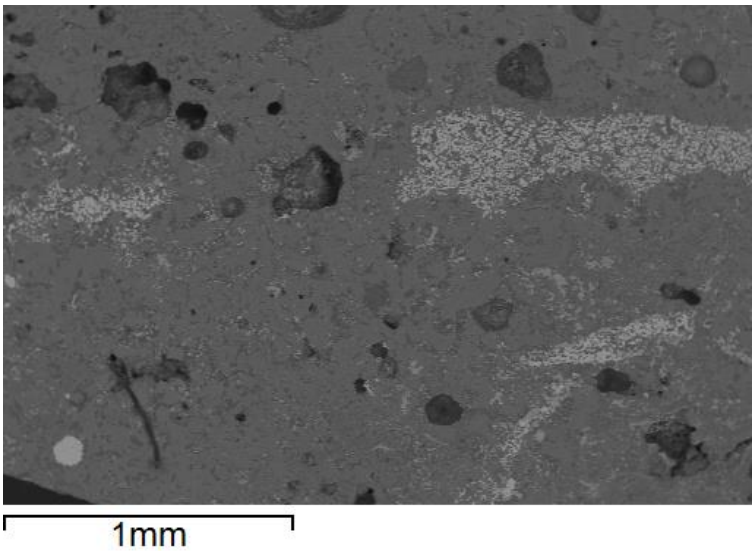

Figure 8.23: SEM-BSE image of the reduced iron metal particles (white) inclusions of the slags from Kalenga area (sample 1-2SE2). Note blocky monticellite (grey), glass (dark grey), and porosity (black)

8.3.3.8 Leucite crystals

While only one and two slag samples from Ngongwa site #1 and Magubike site #1 respectively had leucite ($KAlSi_2O_6$, or $K_2O.Al_2O_3.2SiO_2$) crystals, virtually all the samples at Magubike site #2 contained these (Table 8.15). The leucite crystals are black phases in between fayalite (or monticellite) crystals and sometimes with (secondary)

wüstite in them (Figure 8.24). They are all virtually pure crystals, because the three compounds of this mineral: K_2O, Al_2O_3, and SiO_2 combine to the ratio of 1:1:2 respectively (see Table 8.15). Also, they contain about 4.2 wt% FeO, 0.7 wt% Na_2O, and 0.3 wt% TiO_2.

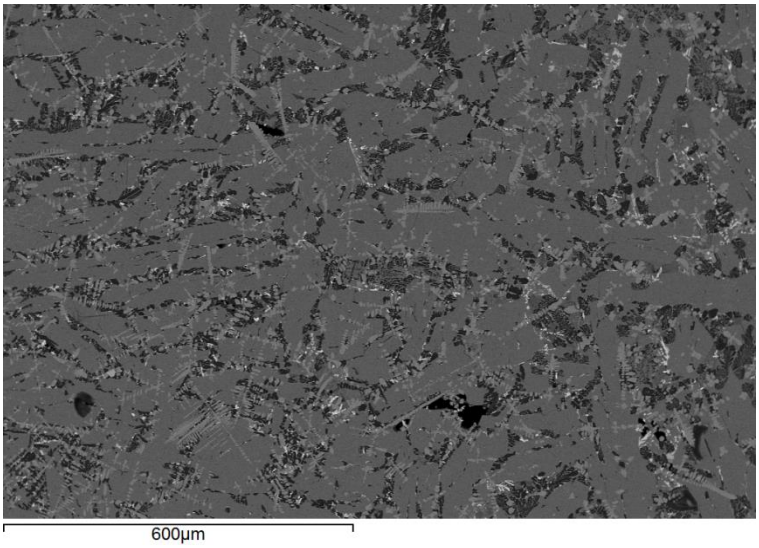

Figure 8.24: SEM-BSE image of leucite crystals (light black) in the Kalenga smelting slags (sample 2SE4). Note blocky fayalite (grey), wüstite (bright grey), zirconia (bright white), glass (dark grey), and porosity (black)

Table 8.15: SEM-EDS chemical composition (in wt%) of leucite in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Na_2O	Al_2O_3	SiO_2	K_2O	TiO_2	FeO	Total
Smelting slags from Ngongwa site #1								
1	1SA1	0.6	21.9	55.6	20.0	0.3	1.6	100
Smelting slags from Magubike site #1								
2	1-2SE2	1.2	28.8	39.6	26.9	0.1	3.4	100
3	1-4SE5	0.9	21.2	54.6	20.8	0.0	2.5	100
Smelting slags from Magubike site #2								
4	2SE1	0.6	20.4	53.8	17.9	0.2	7.0	100
5	2SE2	0.6	20.1	52.2	18.5	0.7	7.8	100
6	2SE3	0.8	21.4	53.1	19.8	0.6	4.2	100
7	2SE5	0.5	21.6	54.9	20.2	0.3	2.4	100

8.3.3.9 Porosity, quartz, and other crystals

All the slag samples from this area were relatively less porous, and two samples alone from Magubike site #1 had some sand quartz inclusions (see Table 8.11). In addition, two samples from Ngongwa site #1 and one sample from Magubike site #2 contained supposedly small (magnetite) grains (Figure 8.25). Based on the chemical composition (Table 8.16), it is unlikely that these were part of the smelted ores at the sites, because they contain relatively high titania about 15 wt%, while the bulk area composition data (see Table 8.9) indicated as low as 1 wt% titania. Also, the sample from Magubike site #2 contains very low zirconia about 0.2 wt%, while the bulk area compositional data had as high as 3 wt% zirconia, on average. More likely, these fragments were accidentally incorporated into the slags.

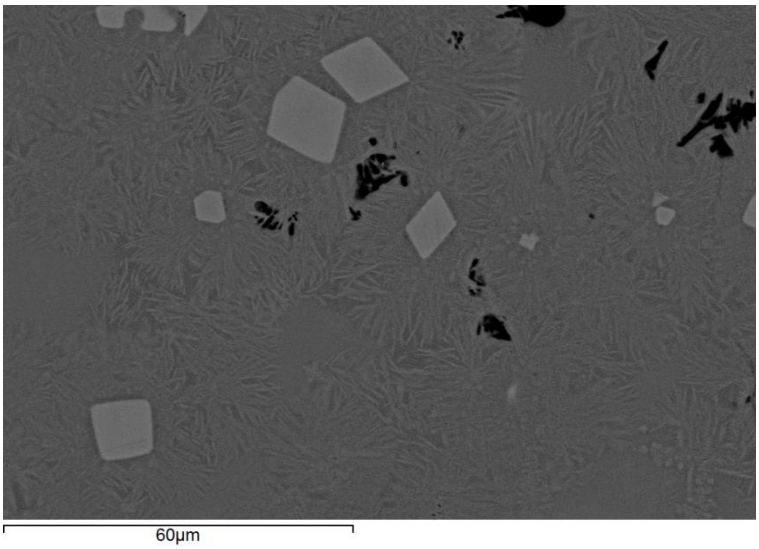

Figure 8.25: (Magnetite) grains in the Kalenga slags. Note the photomicrograph was taken at 1000x.

Table 8.16: SEM-EDS chemical composition (in wt%) of grains in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Al_2O_3	SiO_2	CaO	TiO_2	V_2O_5	Cr_2O_3	FeO	ZrO_2	Total
1	1SE7	4.7	0.5	0.0	12.7	2.1	0.9	76.9	2.1	100
2	1EA1	6.6	1.0	0.3	16.4	2.3	0.6	69.1	3.6	100
3	2SE2	7.1	0.3	0.0	1.1	1.9	6.6	82.8	0.2	100

8.4 Discussion of the Aims of the Chapter

In the second chapter (see Previous Archaeological Knowledge in Rural Iringa), I outlined five aims of this chapter. To recap, they are (1) exploring the nature of the technical ceramics, (2) finding out furnaces air supply mechanism, (3) investigating techniques of handling the liquid slag while smelting iron, (4) examining iron reduction efficiency and the associated factors, and (5) suggesting the nature of the final smelting product from this area. Below I briefly discuss these aims based on both the macroscopic and microscopic data presented earlier.

First, the iron smelters of Kalenga selected different clays to manufacture the furnace clay rolls, pottery, and tuyères (see Figure 8.12; Figure 8.13). Although the test briquettes (TBs) are chemically less similar to the furnace clay rolls, with more silica concentration (see Figure 8.12), I strongly think (by intuition) that the WPs were sources of clays for the furnace clay rolls as well. The chemical mismatch between the two could have been due to the problem of sampling leached clays for the TBs, because the samples were collected from the centre of the WP where sand quartz was deposited from elevated edges. Unless other sources of clay for the clay rolls are convincingly discovered elsewhere nearby the sites, it is difficult to understand why the WPs at the smelting sites (except Magubike site #1) have depressions. Supposedly, they deepened

because clay for the rolls was dug from them. The sources of clay for the pottery and tuyères are yet to be discovered, because they are not from the WPs.

The selection of different clays for the technical ceramics was perhaps based on the refractory quality of the ceramics. This is not unexpected, because they were used for different technical purposes operating at different temperatures (see Freestone and Tite 1986; Freestone 1989; Hein *et al*. 2007). The absence of completely bloated ceramics at the sites indicates that the technical ceramics were *all refractory* and less subjected to their temperature limits. Nonetheless, the tuyères at both Ngongwa #1 and Magubike #2 sites were generally more refractory than the furnace rolls, possibly because the former were subjected to relatively higher temperatures than the furnace walls (see Freestone and Tite 1986; Childs 1989a; Schmidt 2006). For the same reason, the smelters preferred more silica concentration in the tuyères than in the furnace rolls (see Figure 8.13) so as to maximize their thermal shock resistance since high quartz concentration decreases the fracture strength of a ceramic body (see Tite *et al*. 2001: 307, 315). The pottery was subjected to relatively low temperatures beneath the furnace, assuming that it was used for ritual purposes (e.g. Schmidt 1997a, 2006; Mapunda 2010). It is noteworthy that sometimes the pottery may have not been subjected to heat for it could have been used for ritual purposes or other personal uses outside the furnaces.

Second, it seems that air supply into the smelting furnaces of Kalenga was executed through bellows. This proposition is based on the presence of excellent flared tuyères at all the sites, because the trumpeted ends were receptacles for the bellows (e.g. Childs 1996; Mapunda 2010). Elsewhere in Ufipa Tanzania, the lack of flared tuyères at a smelting sites, among other factors, has been used to conclude that *Katukutu* were natural draft smelting furnaces (e.g. Mapunda 2010: 126). In addition to the flared ends, other factors, especially the size and height of the respective furnaces, are important

(see van der Merwe and Avery 1987: 149). In our case, the proposed two or three tuyère ports per furnace based on the relatively small external diameters, about 46 cm on average, makes it difficult to believe that the Kalenga furnaces could have been operated by a natural draft mechanism conventionally associated with large and tall smelting furnaces of central and east Africa (e.g. van der Merwe and Avery 1987; Gordon and Killick 1993; Barndon 2004; Mapunda 2010).

Third, I have both the macroscopic and microscopic data to strongly suggest that the liquid smelting slag was left to drain down into the slag-pit at the bottom of the furnaces. Macroscopically, the lump of intact slag in the remnants of the furnace at all the Kalenga sites (excluding Magubike site #1) indicates that the furnaces were non slag-tapping structures, because slag collected and cooled at the bottom of the furnaces. This indication is further supported by presence of significant number of the droplet slags, which have been used elsewhere in northwestern Tanzania, for example; to support slag-pit furnaces (e.g. Schmidt and Childs 1985: 56). Furthermore, the majority of the smelting slags of this area have relatively very rough surfaces, because if slag flowed and was tapped out of the furnace, correspondingly I would have the majority of the slags exhibiting flow marks with smooth and slippery surfaces (see the previous chapter).

Microscopically, the presence of relatively thick fayalite, monticellite, wüstite, and magnetite crystals in the smelting slags strongly indicates that the slags cooled so slowly that they had sufficient time to grow thick, and that the slow cooling would have simply happened in less oxidizing conditions more likely underneath the smelting furnace (e.g. Severin *et al*. 2011). The latter has been attested by the absence of (oxidised) tap lines in the slags of this area, although some slags have (unoxidised) tap-

like lines (Figure 8.26) equally suggesting that the slags were not exposed to the ambient air.

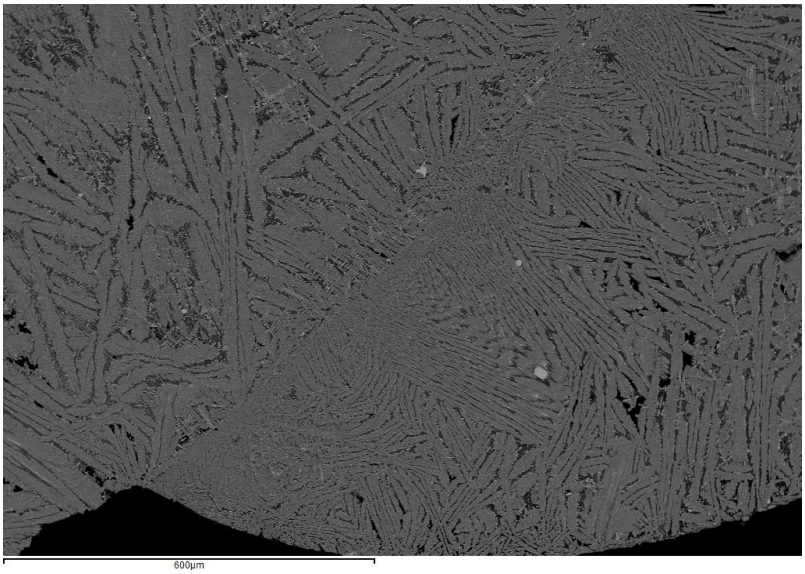

Figure 8.26: SEM-BSE image of unoxidized tap-like lines in some of the Kalenga slags (sample, 1SE5)

Fourth, although a forced draft furnace would generally be thought technically more efficient than a natural draft one (see Gordon and Killick 1993: 261), the forced draft furnaces of Kalenga were relatively and generally inefficient, because none of the samples from the three sites plotted into the optimum 1 region (see Rehren *et al*. 2007). The slags of Ngongwa plot distant but relatively closer to optimum 1 than to optimum 2 region, and the samples from Magubike site #1 and #2 plot closer to Optimum zone 2 (see Figure 8.14). The inefficiency of the smelting process may have prevailed for a long time, since the mid-2nd millennium AD up to historic times, albeit there was a relative small improvement, from the least reduction efficiency (Magubike site #1) to the more efficient (Magubike site #2) process. This slight temporal improvement in the reduction efficiency was perhaps associated, among other things, with the change of charge raw materials, from Ca-rich to Zr-rich load. Unfortunately the smelters did not fully achieve the goal even with the change of the charge raw materials. There must

have been other factors such as low fuel to ore ratio and less control of the smelting temperatures contributing to supposedly low yields. Low fuel to ore ratio, among other effects, is likely to reduce yields and increase iron oxides of the slags (Tylecote *et al*. 1971: 352). Also, even if air supply into the furnace is efficiently done, the use of bricks or clay rolls could have affected optimum temperature maintenance in the furnaces, because expansion and contraction due to heating and cooling is likely to loosen the space between the clay rolls; that in turn allows cool air to be drawn into the furnace as well as allowing some gas to escape from the furnace, albeit at low levels (see Tylecote *et al*. 1971: 351). If these factors had been recognised and controlled properly, the iron yield would have increased.

Finally, the iron smelters of Kalenga could have aimed at producing steel or iron. To produce steel, they firstly needed sufficient and optimum reducing conditions in the furnaces to reduce all the iron oxides and agglomerate these into a lump of iron, and secondly, a high fuel to ore ratio would have been necessary for this to happen (e.g. van der Merwe and Avery 1982; Schmidt 2006). When these conditions, among others, are sustainably well met, the resultant slags will be glass-like with none or little (secondary) wüstite crystals, sometimes with (a few) iron metal droplets (e.g. Tholander and Blomgren 1985; Tholander 1989). Because the slags of Kalenga had (primary) wüstite and no iron droplets were observed, it is more probable that steel was not produced at these sites.

Alternatively, the frequent occurrence of wüstite crystals including magnetite and (angular) iron particles indicates that there were insufficient reducing conditions in the furnaces for complete reduction and agglomeration of all the reduced iron particles into a lump of iron metal. Such conditions could not have produced steel, but all the reduced and agglomerated iron was soft iron. Elsewhere, in Sweden, for example, the slag

features, including irregular shaped iron micrograins, have been used to characterise a low bloomery process, whose final product was a 'bloomery' iron (e.g. Tholander and Blomgren 1985: 422; Tholander 1989: 38). Therefore, there is almost no doubt that the smelters at the Kalenga sites aimed at producing soft iron, and not steel, but the yield could have been low.

8.5 Summary

The main aim of this chapter was to examine spatial and temporal variation in the iron production techniques in Kalenga. There is little temporal change in terms of iron reduction efficiency between Magubike site #1, and Ngongwa site #1 and Magubike site #2 smelting processes. The former had the less reduction efficient process, while the latter had relatively the more reduction efficient processes, albeit they did not reach Optimum zone 1. It appears that the ancient smelters in Kalenga did not fully reach the desired end, possibly because they failed to increase the fuel to ore ratio and to change the furnace forms.

In terms of spatial distribution, the (later) iron smelting processes in Kalenga were similar in the use of small, forced draft, and non-slag tapping furnaces made of clay rolls, the use of short and flared tuyères, the use of Zr-rich iron ores, and the presence of the WP at all the smelting sites. Also, the smelters were clay selective in order to produce technical ceramics, and selected refractory clays of which tuyères were the most refractory ceramics followed by furnace rolls and pottery. In this respect, the smelters had good skills.

9. Iron Production in Njombe

9.1 Preamble

This chapter focuses on recent iron production in Njombe district located in the Iringa region (Figure 9.1). The indigenous people are the majority Bena (LOT 2009: 20), a Bantu-speaking tribe (Sutton 1971), and Ubena refers to the land of Bena (Nyagava 1988, 1999). The chapter is organised into four sections. The first two focus on the presentation and interpretation of new macroscopic and microscopic data. The following two sections discuss the aims of the chapter in line with both macroscopic and microscopic data. Finally, the summary condenses the main focus of the chapter.

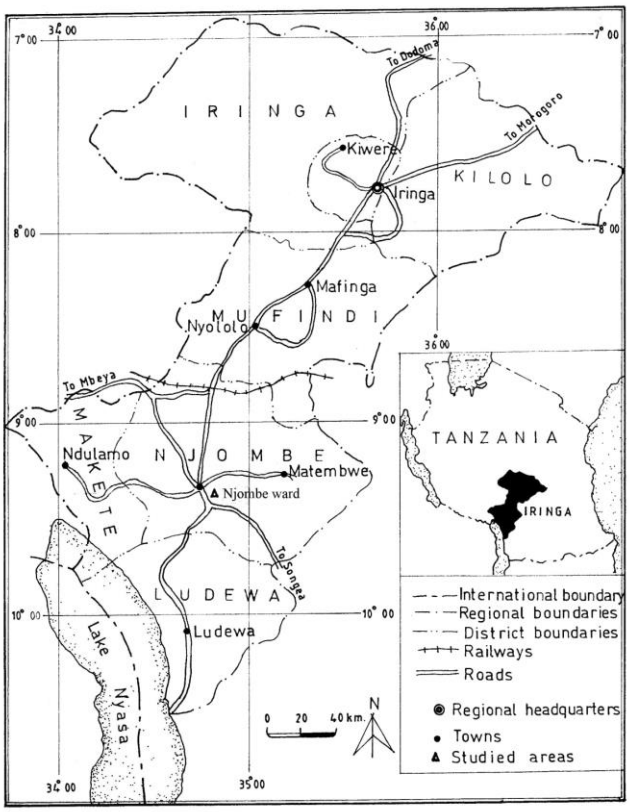

Figure 9.1: Map of Iringa showing the location of Njombe ward

9.2 Presentation and Interpretation of Macroscopic Data

9.2.1 Sites: Location, Size, Preservation, and Context of the Material

9.2.1.1 Location

Fieldwork in Njombe was conducted in Njombe ward, located about seven km South of Njombe town along the Songea road, and five km off the main road (see Figure 9.1). In this ward, a total of five iron smelting sites, and one smithing site were discovered in three villages, namely, Mjimwema, Msete, and Nundu (see Appendix 9.1). The sites are generally located at about 1807 m (on average) above mean sea level. They are all situated within 66 m of nearby water sources (Figure 9.2), in order to get close to the *mdapu* ore (see also Msemwa 2001; Sutton 1985).

Figure 9.2: Sketch site map of the Njombe smelting and smithing sites

9.2.1.2 Area size

On average, the smelting and smithing sites have an area of about 28 m^2, which is significantly smaller than all the previous smelting sites. The Nundu smithing site had a relatively larger area than the smelting sites. The widespread occurrence of scale and droplet slags suggests that it was probably occupied for a relatively long period of time (Figure 9.3). Although the relatively small size of the smelting sites could be related to a short period of occupation, the possibility that some of the smelting slags have been eroded into the river is high, since the sites are located on slopes in the river valleys. Another possibility is that the smelting slags and other debris were discarded or rather buried in (technical) pits, because careful field observation suggests that about three quarters of the smelting debris of Msete SE1 were buried before being exposed while digging the walls of the HEP water tunnel (Figure 9.4) by John Akin Fute.

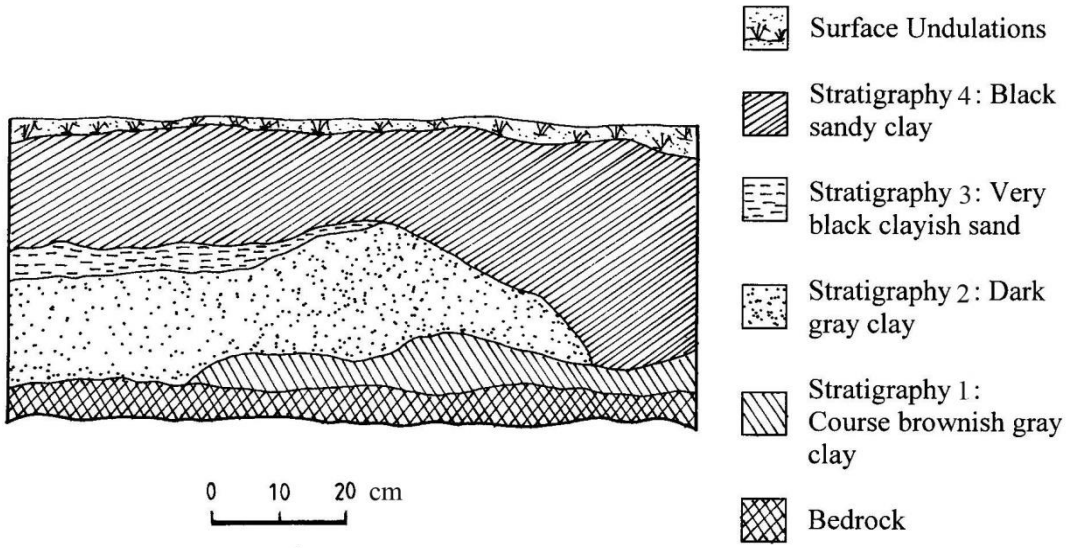

Figure 9.3: Southern wall profile of Nundu ST1 Unit 1

Figure 9.4: Slags and tuyères of Msete #1 site projecting from the HEP water tunnel

9.2.1.3 Preservation

All the sites of this area are located away from farms, which has left them almost undisturbed by people, albeit some of the smelting and smithing debris have been naturally disturbed by water erosion down the river valleys. Because of the latter, some of the slags can be found on the banks of the river. Fortunately, Msete and Nundu smelting sites are located in a well-forested area, whose access is limited to the locals. In addition, this area, with 2 smelting furnaces still-standing (Nundu SE2 and SE3), is owned by John A. Fute, who asserts that his parents smelted in this area.

9.2.1.4 Context of the material

The studied material from the smelting sites was all surface collections, while the material from the smithing site was excavated (Table 9.1).

Table 9.1: Summary of the excavated materials (quantity and weight) from Unit 1 at Nundu smithing site #1. Note that 9 pottery (200 g), 904 charcoals (226 g), and 18 iron metal pieces (80 g) were among the excavated materials at this site.

S/No (Level).	Hammer scales #	Hammer scales wt (g)	Droplets #	Droplets wt (g)	Amorphous slags #	Amorphous slags wt (g)	Cake-like slags #	Cake-like slags wt (g)	Tuyères #	Tuyères wt (g)
1	63620	985	295	50	721	3774	15	6750	40	400
2	135360	2260	700	90	1140	2508	12	5400	65	580
3	169200	1689	-	25	1503	28323	13	5850	22	159
4	101520	1715	242	10	770	1140	12	5400	16	282
5	47500	790	145	17	540	751	13	5850	9	201
6	45120	694	57	7	417	609	12	5400	11	199
7	43340	706	40	5	435	466	12	5400	-	-
8	18800	18800	25	7	277	231	12	5400	-	-
9	940	16	-	-	42	78	13	5850	-	-
10	-	-	-	-	790	215	11	4950	-	-
Sum	**625400**	**27655**	**1504**	**211**	**6635**	**38095**	**125**	**56250**	**163**	**1821**

9.2.2 Furnace Attributes

Three (short shaft) smelting furnaces were discovered (Figure 9.5). Based on the dimensions of the furnaces (Table 9.2), Bena iron smelters used short shaft furnaces, about 1 metre high. They have external diameters of about 77 cm at the base, 67 cm in the middle (50 cm), and 50 cm at the top. Internally, up to 50 cm from the base, the furnaces are bell-shaped, possibly referring to a 'pregnant woman' belly, and above 50 cm, the internal diameter remains the same up to the top (Figure 9.6). At the bottom, each of the furnaces had a shallow pit about 10-30 cm deep. While it is difficult to think these were slag-pit provision, they were allegedly used to conceal ritual and medicinal pots (John Akin Fute, interviewed on the 15th September, 2011; for similar practise among neighbouring Pangwa, see also Schmidt 2006: 158). Externally, above the rake hole or birth canal, the furnaces are decorated with anthropomorphic features, especially

of woman breasts (see Figure 9.5, elsewhere see Cooke 1959; Robinson 1961). The breasts, birth canal, and internally bell-shaped furnaces can be used to argue that Bena iron smelting symbolised the human reproduction process (for details, see ethnographic data section). The peep hole for monitoring progress in the furnace was located opposite the birth canal between 30 and 50 cm from the base.

Figure 9.5: Iron smelting furnace at Nundu SE2 in Njombe

Table 9.2: Dimensions of Bena smelting furnaces from Njombe ward. Note SE=smelting, B=base, M=middle, and T=top, E=external, I=internal, WT=wall thickness, D=diameter, and SD=standard deviation.

S/No.	Site	External Diameters			Internal Diameters			Wall thickness			Height	Ports
		EBD	EMD	ETD	IBD	IMD	ITD	BWT	MWT	TWT		
1	Msete SE4	76	67	50	30	31	30	23	18	10	110	3
2	Nundu SE2	78	66	48	32	32	31	23	17	8.5	108	3
3	Nundu SE3	77	67	49	33	32	30	22	17.5	9.5	107	3
4	**Average**	**77**	**67**	**49**	**32**	**32**	**30**	**23**	**18**	**9**	**108**	**3**
5	**SD**	**1**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**2**	**0**

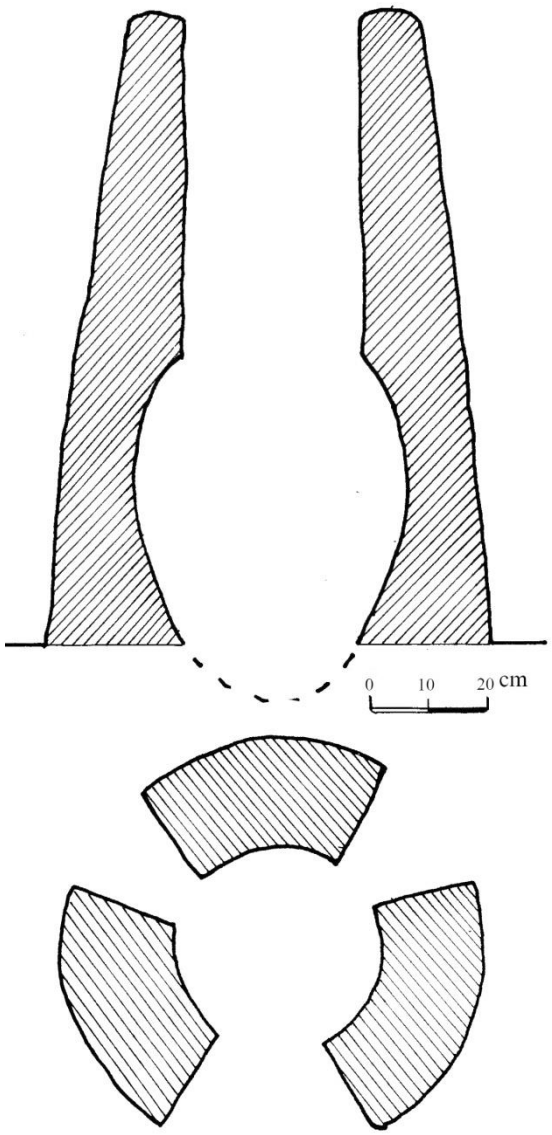

Figure 9.6: Sketch of Bena iron smelting furnaces

9.2.3 Tuyère Ports and Tuyères

9.2.3.1 Tuyère ports per furnace and tuyères per port

As noted above, the furnaces of Ubena had three tuyère ports. According to the oral evidence (see Appendix 4.2e), the first 2 functioned as draught tuyères ports alone, while the third, in addition to the draught function, was used as a rake hole at the end of the smelt. It measured 30 cm both in width and height, while the ordinary tuyère ports measured 15 cm and 19 cm in width and height respectively. Unlike the Matengo, each

of the ports housed one tuyère. According to the respondents, no tuyères were used for slag tapping, and instead, a small *mlepulo* hole was opened up below the tuyères level to tap the slags (for similar practice among the neighbouring Pangwa, see Schmidt 2006: 159). It was unclear from the respondents, however, whether or not the tapped slag was drained into another deep pit. If they flowed freely on the surface cooled rapidly as opposed to relatively slow cooling in the pit (for details on this, see mineralogical data section).

9.2.3.2 Tuyère attributes

The tuyères recovered were body and distal segments, measuring 6 to 8.5 cm, 3.5 to 4.5 cm, and 1 to 1.5 cm in external diameter, internal diameter, and thickness respectively (Table 9.3). Based on their dimensions, the tuyères of Ubena (Figure 9.7) are relatively more massive than the Kigonsera and Kalenga tuyères, with an average of about 6 cm and 3 cm for external and internal diameters respectively (see the previous two chapters). Some of the distal ends were slag-coated, occasionally with slag run-back. Generally, the tuyères have sand quartz inclusions, and are whitish, suggesting use of more refractory clays (for details, see chemical data section).

Although no tuyères with proximal ends were found to suggest a forced draft operation (see Mapunda 2010: 126), based on the relatively short height of the furnaces and the 3 tuyère ports, it is more probable that these furnaces were operated by bellows (see van der Merwe and Avery 1987: 149). For a natural draft operation to be technically efficacious, a height of at least 1.5 metres is needed. The forced draft interpretation was further supported by the oral evidence (for a similar view, see also Mapunda 2010: 68).

Table 9.3: The macroscopic attributes of the tuyères from Njombe ward sites. Note that ED=external diameter, ID=internal diameter, and SD=standard deviation.

S/No.	Site	ED (cm)	ID (cm)	Thickness (cm)	Remarks
1	Msete SE1	6.5	3.5	1.2	slag-coated
2	Msete SE1	6.4	3.5	1.3	
3	Msete SE1	7	3.7	1.2	
4	Msete SE2	7.2	3.8	1.3	
5	Msete SE2	6.7	3.7	1.4	slag-coated
6	Msete SE2	6.3	3.7	1.4	
7	Msete SE3	8	4.1	1.3	slag-coated
8	Msete SE3	7	4.2	1.2	
9	Msete SE3	7.5	4.3	1.3	
10	Nundu ST1	6	3.5	1.3	
11	Nundu ST1	6.3	3.5	1.4	
12	Nundu ST1	6.2	3.5	1.1	
13	Nundu SE3	7.6	4.5	1.2	slag-coated
14	Nundu SE3	7.8	4.4	1.3	
15	Nundu SE3	8.5	4.4	1.6	slag-coated
16	Nundu SE2	7.6	4	1.5	
17	Nundu SE2	7.9	4	1.4	
18	Nundu SE2	8	4.3	1.5	slag-coated
19	**Average**	**7**	**4**	**1**	
20	**SD**	**0.8**	**0.4**	**0.1**	

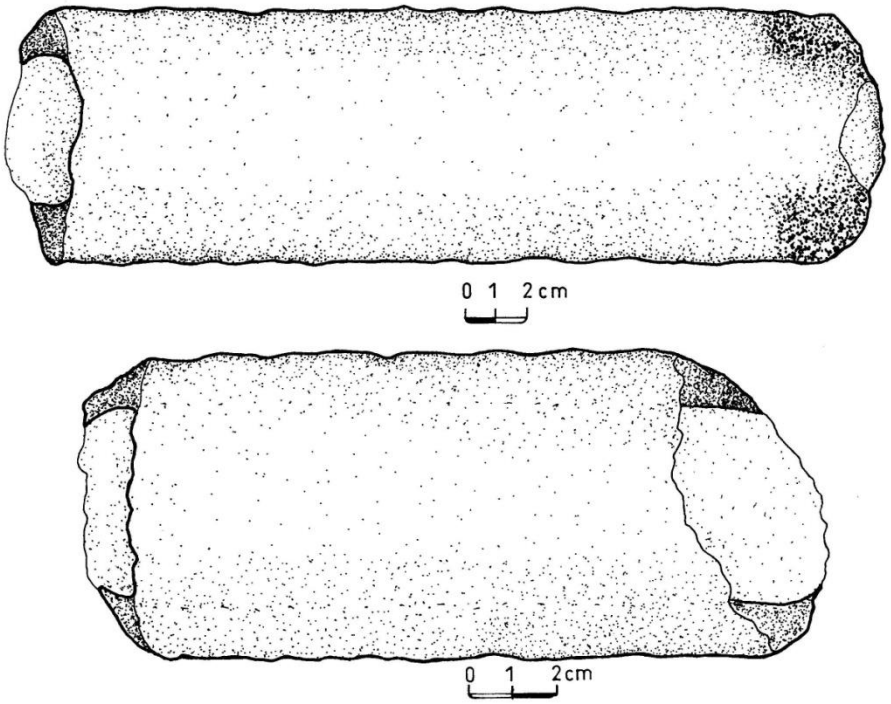

Figure 9.7: Tuyères of Ubena

9.2.4 Slag Attributes

9.2.4.1 Smelting slags

Based on morphology, the smelting slags of Ubena can be divided into four groups, namely, cake-like (Figure 9.8), blocky slags with several conspicuous flow marks (Figure 9.9), small flow slags, and droplet slags. Tables 9.4 through 9.6 present attributes of the first three groups. On average and based on the attributes, the blocky slags are larger in size and heavier than both cake-like and small flow slags. The few solid droplet slags I discovered were about 3-10 mm in size and weighed about 1-4 g each. The paucity of droplet slags and conspicuous flow marks at the sites are a strong indication of the use of non-slag-pit furnaces, a practice attested by oral evidence as well (see also mineralogical data section). It is noteworthy that slag tapping was not done through the tuyères, because no tuyère mould slags were recovered, and informants have correctly affirmed that it was through the *mlepulo* hole.

In addition, while the cake-like smelting slags are brownish, somewhat corroded, and magnetic, the flow smelting slags and droplets are relatively greyish, less corroded, and less magnetic. The former are more magnetic than the latter, because they were presumably close to the smelted iron, and highly magnetic slags become corroded easily and surface colours go brownish, yellowish or reddish quickly **(**and vice versa**)**.

9.2.4.2 Smithing slags

I discovered a smithing site largely with hammer scales, (hollow) droplets, and agglomerated slags (see Figure 9.10). As well as the slags, there were anvils with dolly holes, and hammers at the site. Detailed macroscopic attributes of these slags have been reported elsewhere (see Lyaya 2007, 2008b, 2011). For the purpose of this work, it suffices to note that both smelting and smithing processes in this area were secluded from settlements and strangers, and that the Bena practised a two-stage iron production process: smelting and smithing, without a refining stage between the two (see Mapunda 2010: 69; Lyaya 2011).

Figure 9.8: Example of the smelting cake-like slags from Msete in Njombe

Figure 9.9: Blocky smelting slags with (conspicuous) flow marks from Ubena

Table 9.4: Macroscopic attributes of cake-like smelting slags from Ubena

S/No.	Site	Mass (Kg)	Length (cm)	Width (cm)	Thickness (cm)
1	Msete SE1	2	17	15	7
2	Msete SE1	2	23	13	9
3	Msete SE2	1.3	19	13	6
4	Msete SE2	1.4	11	9	8
5	Msete SE3	1.5	17	11	7
6	Msete SE3	0.6	12	10	6
7	Nundu SE2	0.8	11	9	6
8	Nundu SE2	0.4	10	10	5
9	Nundu SE3	0.3	8	6	4
10	Nundu SE3	0.3	9	6	3
11	**Average**	**1**	**14**	**10**	**6**
12	**SD**	**0.7**	**5**	**3**	**2**

Table 9.5: Macroscopic attributes of blocky smelting slags from Ubena

S/No.	Site	Mass (Kg)	Length (cm)	Width (cm)	Thickness (cm)
1	Msete SE1	4.3	19	12	8
2	Msete SE1	2.1	18	12	9
3	Msete SE2	1.1	15	11	6
4	Msete SE2	6	18	10	10
5	Msete SE3	9.6	30	21	7
6	Msete SE3	4.8	11	8	5
7	Nundu SE2	7.9	12	6	5
8	Nundu SE2	1.4	12	8	7
9	Nundu SE3	6.2	10	6	5
10	Nundu SE3	2.8	10	5	4
11	**Average**	**5**	**16**	**10**	**7**
12	**SD**	**3**	**6**	**5**	**2**

Table 9.6: Macroscopic attributes of (small) flow smelting slags from Ubena

S/No.	Site	Mass (g)	Length (cm)	Width (cm)	Thickness (cm)
1	Msete SE1	600	7	2	1
2	Msete SE1	830	6	3	2
3	Msete SE2	525	8	4	2
4	Msete SE2	640	9	3	2
5	Msete SE3	390	7	2	2
6	Msete SE3	240	10	2	2
7	Nundu SE2	165	6	3	2
8	Nundu SE2	110	8	4	2
9	Nundu SE3	50	6	5	3
10	Nundu SE3	170	5	3	2
11	**Average**	**372**	**7**	**3**	**2**
12	**SD**	**265**	**1.5**	**1.0**	**0.5**

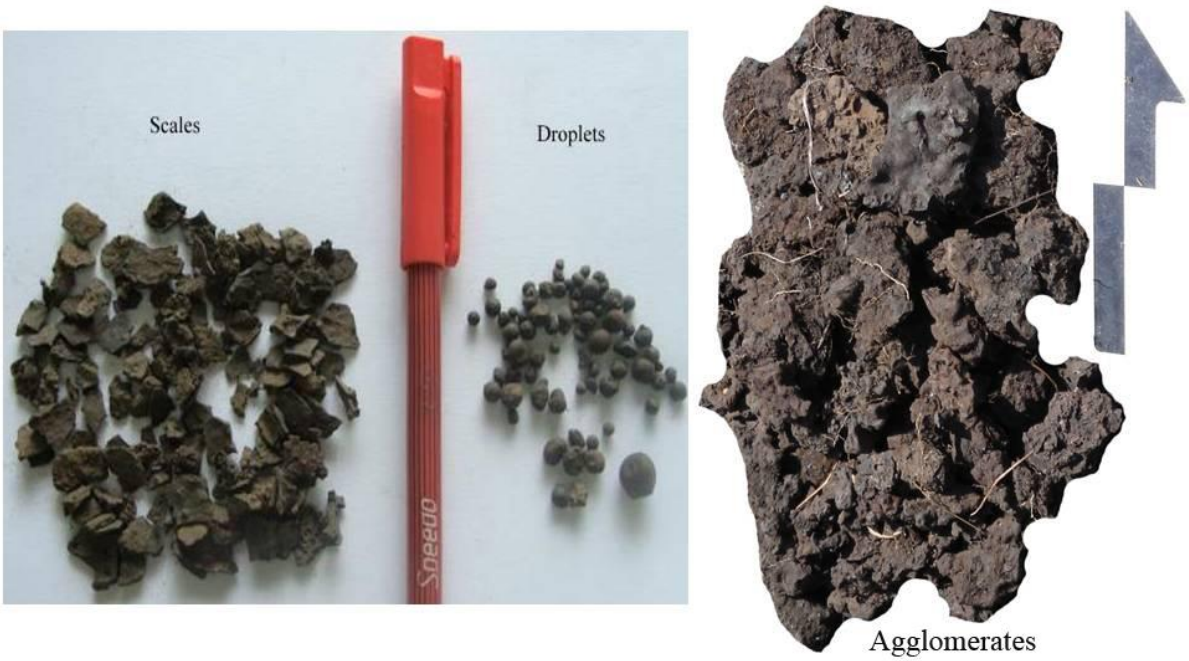

Figure 9.10: Smithing slags from Nundu (ST1) in Njombe ward

9.2.5 Pottery

Nine undecorated pieces of pottery were collected from the Nundu smithing site, and six broken pots were collected from Nundu smelting site #2 (Figure 9.11). The context in which they were found suggest that they were part of the ironworking process, either for ritual and medicinal purposes or as food or water containers for the smelters, among other uses. These were chemically examined to find out whether the manufacturers used different clays from those used to manufacture and construct other technical ceramics.

Figure 9.11: Broken pots from Nundu site #2 in Njombe

9.3 Presentation and Interpretation of Microscopic Data

9.3.1 Technical Ceramics Chemical Data

Table 9.7 presents the major and minor oxide concentrations of the tuyère, pottery, and furnace samples from Msete 1 and Nundu 2 smelting, and Nundu 1 smithing sites. There is relatively more silica concentration in the tuyères of Nundu 2 than in the tuyères of Msete 1 and Nundu 1 sites, while alumina is more concentrated in the tuyères of Nundu 1 than in the tuyères of Msete 1 and Nundu 2 sites. Furthermore, the tuyères of Msete 1 have relatively more iron, magnesia, titania, and sulphide than the tuyères of Nundu 1 and Nundu 2 sites (see Table 9.7).

In addition, there is no significant difference in trace oxide concentration, although there is relatively more copper, zinc, zirconium, barium, and lead oxide concentration in the tuyères of Msete 1 than in the tuyères of Nundu 1 and 2 (Table 9.8). Rubidium and tungsten oxides are more concentrated in the tuyères of Nundu 1 and 2 respectively than in the Msete 1 tuyère samples. The slight chemical differences suggest that the clays for

the tuyères probably came from a similar source, with a similar (maximum) refractory quality of about 1700 ^{o}C (Figure 9.12).

Secondly, on average, there is a relatively higher concentration of silica, iron, titania, magnesia, and lime in the pottery of Nundu 2 than those of Nundu 1. On the other hand, the pottery of Nundu 1 is more concentrated in alumina, potash, phosphate, and sulphide than the pottery of Nundu 2. Also, there is no major difference in trace oxide concentration, although there is relatively more cobalt, nickel, copper, and tungsten oxide concentration in the pottery of Nundu 1, and more rubidium, strontium, and barium oxide concentration in the pottery of Nundu 2 than in the pottery of Nundu 2 and 1 respectively (see Table 9.8). Besides these slight differences, they apparently had similar maximum refractory quality between 1600 and 1700 ^{o}C.

Lastly, on average, the furnace walls of Nundu 2 had relatively higher concentrations of silica and potash in the furnace walls than in the tuyères and pottery, while alumina was more concentrated in the tuyères than in the furnaces and pottery. Apart from that, iron, titania, and lime are more concentrated in the pottery than in the tuyères and furnaces. In terms of the trace oxides, there is relatively more nickel, copper, rubidium, strontium, and barium oxide concentration in the pottery, and more zirconium and tungsten concentration in the tuyères than in the furnaces and tuyères and pottery and furnaces respectively (see Table 9.8). Based on the data, it is more probable that different clays were selected for the construction of the smelting furnaces and manufacturing of tuyères and pottery. This proposition is further strengthened by the notable differences in the refractory quality of the three sets of technical ceramics, while tuyères were the most refractory, pottery were the least refractory ceramics, and furnace in between the two (Figure 9.12).

Table 9.7: (P) XRF-EDS Major and minor oxide concentrations (in wt%) of the technical ceramics from Msete and Nundu sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 9.2, TYR=tuyère, FW=furnace wall, and PTR=pottery

S/No.	Sample/ Oxides	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	AT
Technical ceramics from Msete smelting site #1													
1	1TYR1	0.24	0.52	23.23	71.02	0.04	1.80	0.15	0.83	0.01	0.02	2.15	97.62
2	1TYR2	0.17	0.63	28.01	64.53	0.07	1.53	0.07	0.96	0.01	0.02	4.00	97.40
3	1TYR3	0.27	0.59	24.54	68.73	0.04	2.07	0.20	0.81	0.01	0.02	2.71	97.44
Technical ceramics from Nundu smelting site #2													
4	2FW1	0.23	0.38	21.63	70.81	0.04	3.65	0.02	0.43	0.01	0.03	2.78	98.55
5	2FW2	0.19	0.42	22.79	69.36	0.05	3.61	0.04	0.50	0.01	0.03	3.02	98.51
6	2FW3	0.18	0.43	23.14	69.27	0.05	3.60	0.03	0.44	0.01	0.02	2.82	98.40
7	2PTR1	0.24	0.90	24.70	66.01	0.30	3.22	0.41	0.94	0.02	0.02	3.25	98.71
8	2PTR2	0.26	0.97	25.63	64.89	0.30	3.27	0.42	0.95	0.02	0.02	3.28	98.44
9	2PTR3	0.21	0.93	25.46	65.07	0.31	3.30	0.42	0.96	0.02	0.02	3.31	98.70
10	2TYR1	0.22	0.40	28.00	67.06	0.03	1.79	0.08	0.58	0.01	0.02	1.81	96.45
11	2TYR2	0.20	0.41	25.11	70.08	0.03	1.84	0.09	0.53	0.01	0.02	1.68	97.09
12	2TYR3	0.21	0.49	25.05	68.88	0.03	2.08	0.17	0.88	0.01	0.02	2.17	97.34
Technical ceramics from Nundu smithing site #1													
13	N1PTR1	0.27	1.30	24.83	64.85	0.14	1.70	0.54	1.46	0.04	0.03	4.85	98.27
14	N1PTR2	0.18	0.91	22.00	67.93	0.13	1.61	0.58	0.92	0.02	0.03	5.70	99.50
15	N1PTR3	0.21	0.95	20.09	70.49	0.09	1.46	0.54	0.82	0.02	0.03	5.30	99.47
16	N1TYR1	0.25	0.40	28.34	65.71	0.04	1.95	0.22	1.05	0.01	0.01	2.03	96.51
17	N1TYR2	0.19	0.56	27.32	67.46	0.03	2.28	0.08	0.56	0.00	0.01	1.50	96.65
18	N1TYR3	0.19	0.71	28.76	64.40	0.03	3.37	0.13	0.64	0.01	0.02	1.74	96.55

Table 9.8: (P) XRF-EDS Trace oxide concentrations (in ppm) of the technical ceramics from Msete and Nundu sites. Note the results are the average of three runs and are normalised to 100 wt%, the full results in Appendix 9.3, TYR=tuyère, FW=furnace wall, and PTR=pottery

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	Rb_2O	SrO	Y	ZrO_2	Nb_2O_5	Ba	La	Ce	WO_3	PbO	Th
Technical ceramics from Msete smelting site 1																	
1	1TYR1	37	13	36	50	14	56	30	13	220	35	188	7	21	296	17	17
2	1TYR2	32	8	54	56	15	71	19	22	200	35	117	23	46	50	19	23
3	1TYR3	30	10	33	41	13	58	34	16	180	29	180	13	37	155	17	17
Technical ceramics from Nundu smelting site 2																	
4	2FW1	23	4	19	18	11	79	13	17	105	12	183	13	26	40	9	15
5	2FW2	30	4	30	20	12	79	13	15	97	13	176	13	16	39	9	13
6	2FW3	25	4	20	19	11	79	13	16	99	11	172	14	21	40	9	13
7	2PTR1	34	21	46	43	13	85	57	16	115	16	285	12	30	57	15	11
8	2PTR2	25	25	49	42	14	85	57	17	111	16	284	12	30	43	15	11
9	2PTR3	31	22	51	44	14	86	58	17	111	17	288	11	29	40	15	11
10	2TYR1	20	15	23	56	16	55	9	18	118	25	92	12	28	40	12	23
11	2TYR2	45	17	26	37	16	57	10	19	114	24	86	18	39	240	13	20
12	2TYR3	33	16	26	42	14	62	31	10	143	27	209	8	13	268	13	12
Technical ceramics from Nundu smithing site 1																	
13	N1PTR1	51	47	47	37	15	56	58	18	133	14	153	13	28	104	9	6
14	N1PTR2	54	62	87	37	11	56	20	16	113	13	103	13	30	89	17	13
15	N1PTR3	55	57	74	34	10	55	19	16	100	11	106	14	26	102	16	13
16	N1TYR1	31	15	20	41	16	56	40	9	151	30	195	7	9	77	13	13
17	N1TYR2	37	16	27	34	15	67	10	19	109	23	69	14	31	273	11	20
18	N1TYR3	30	19	29	38	18	93	14	23	140	28	103	17	39	198	14	24

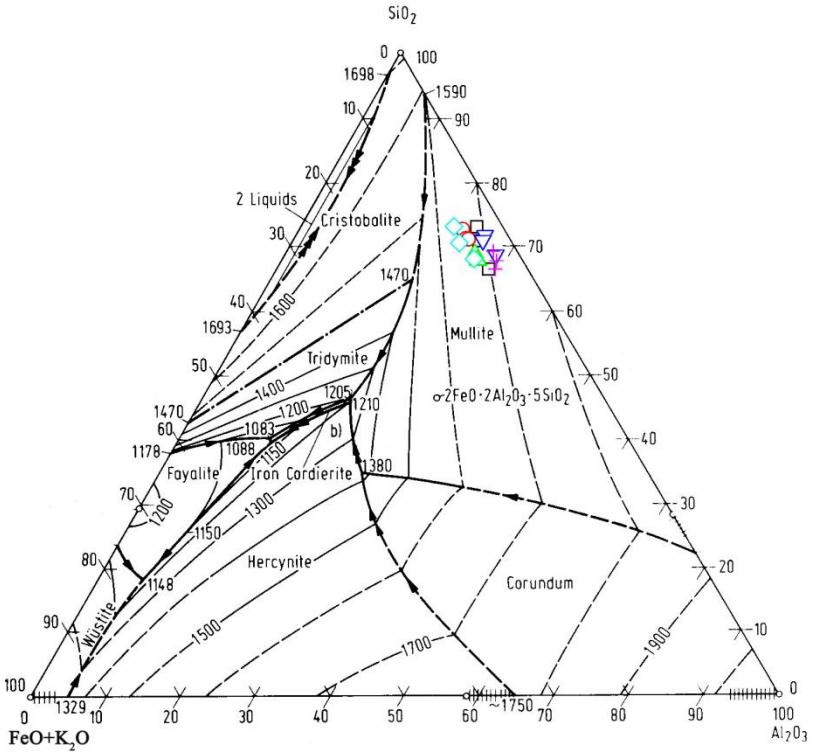

Figure 9.12: Al_2O_3-SiO_2-FeO ternary phase diagram for the technical ceramics from Njombe sites. Note furnaces (red circles), the squares (black), downward triangles (blue), and crosses (purple) are tuyères, and the upward triangles (green) and diamond (sky blue) are pottery

9.3.2 Slag Chemical Data

Table 9.9 presents the concentration of major and minor oxides in the smelting slags from Msete 1 and Nundu 2 smelting sites in order to compare the technological processes of the two villages. On average, the samples contained about 59 wt% FeO, 25 wt% silica, and 6 wt% alumina for both sites, with alumina to silica ratio of approximately 1:4. In terms of reduction efficiency, the Bena smelters in relative terms ensured optimum recovery of iron from the slags. The slag samples plot in the fayalite region, slightly above optimum 2 region (Rehren *et al*. 2007: 212, 214), although one sample plots in the hercynite region (Figure 9.13).

Table 9.9: SEM-EDS major and minor oxide concentrations of the smelting slags from Msete 1, and Nundu 2 sites. The results are the average of three areas measured at *x*50 and are normalised to 100 wt%; the full results in Appendix 9.4

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	Total
Smelting slags from Msete 1											
1	1SE1	0.6	5.5	19.1	0.9	1.7	6.1	0.5	0.4	65.2	100
2	1SE2	0.6	5.5	26.7	1.2	1.7	3.7	0.2	0.3	60.0	100
3	1SE3	0.6	6.0	25.2	1.4	2.8	5.2	0.5	0.4	57.8	100
4	1SE4	0.6	5.1	29.4	1.1	3.2	5.9	0.6	0.4	53.8	100
5	1SE5	0.8	5.8	24.5	1.6	2.7	3.9	0.2	0.4	60.0	100
Smelting slags from Nundu 2											
6	2SE6	0.6	5.6	22.8	1.3	1.5	3.5	0.3	0.4	63.9	100
7	2SE7	0.6	5.1	24.8	1.0	1.8	5.5	0.5	0.4	60.3	100
8	2SE8	0.9	6.6	22.2	1.4	2.2	6.6	0.5	0.4	59.2	100
9	2SE9	0.7	10.8	25.8	2.4	1.9	7.1	0.7	0.3	50.3	100
10	2SE10	0.7	5.9	24.2	1.3	2.2	4.6	0.4	0.4	60.3	100

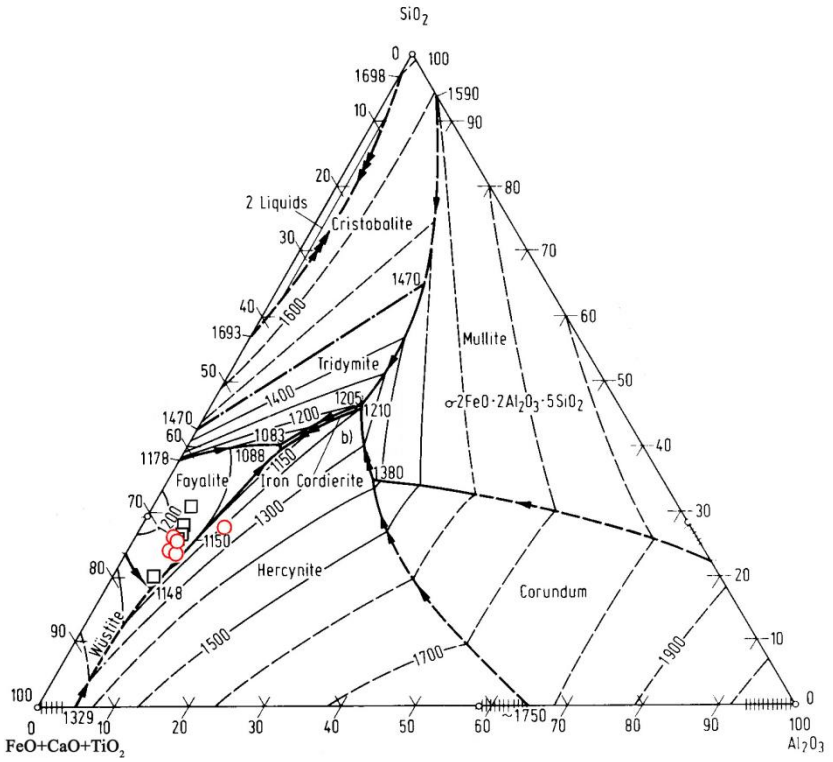

Figure 9.13: Al_2O_3-SiO_2-FeO ternary phase diagram for the smelting slags from Msete 1 (black squares), and Nundu 2 (red circles) sites

Furthermore, titania concentration is about 5.5 wt% for both sets of slags samples suggesting that the black sands mentioned in literature (e.g. Sutton 1985) were actually titanium-rich iron ores, with some vanadium and manganese concentration of about 0.5 wt% each on average. The proposed use of similar iron ores is further strengthened by similar concentration of the trace oxides across the sites (Table 9.10). Moreover, the concentration of the fuel ash indicators including magnesia, potash, and lime are similar for both sets of samples. The similarity in the chemical data suggests that the Bena iron smelters had similar skills and experience, smelted similar titanium-rich ore, and whose process in terms of operating parameters was perhaps similar as well.

Table 9.10: (P) XRF-EDS Trace oxide concentrations (in ppm) of the smelting from Msete 1, and Nundu 2 sites. Note the results are the average of three runs and are normalised to 100 wt%; the full results in Appendix 9.5

S/No.	Sample/ Oxides	Co_3O_4	NiO	CuO	ZnO	Ga	SrO	Y	ZrO_2	Nb_2O_5	Ba	Ce	Hf	Ta_2O_5	WO_3	Th	U
Smelting slags from Msete 1																	
1	1SE1	172	11	77	8	28	103	12	61	10	86	17	17	21	18	14	15
2	1SE2	194	10	80	15	25	87	12	73	13	72	16	16	18	16	13	14
3	1SE3	150	10	62	4	18	148	14	63	13	97	16	15	17	17	12	13
4	1SE4	150	10	59	5	26	206	14	71	15	92	22	15	21	15	12	11
5	1SE5	150	9	60	4	17	147	13	63	16	114	21	15	18	16	13	14
Smelting slags from Nundu 2																	
6	2SE6	159	10	76	19	19	101	13	70	14	82	15	17	24	16	13	10
7	2SE7	150	10	63	16	18	112	12	63	8	93	16	17	27	19	12	13
8	2SE8	150	10	56	6	24	152	13	73	12	135	12	14	16	39	12	12
9	2SE9	132	8	111	16	21	89	14	45	10	138	14	16	19	15	9	12
10	2SE10	150	10	70	7	20	113	13	84	16	72	16	15	20	32	12	11

9.3.3 Slag Mineralogical Data

Table 9.11 jointly presents the summary of the microstructures of the smelting slags from Msete 1 and Nundu 2 sites, for the purpose of comparing further the technological processes of the two areas. To this end, each of the phases is first examined and discussed alone, starting with the fayalite mineral through the quartz grains.

Table 9.11: Summary of minerals of the smelting slags from Msete 1 and Nundu 2 sites.

S/No.	Sample/ Phases	Fayalite	Hercynite	Glass	Ulvite	Wustite	Tap lines	Fe particles	Leucite	Porosity	Quartz	Others
Smelting slags from Msete 1												
1	1SE1	√	-	√	√	√	√	√	-	√	-	-
2	1SE2	√	-	√	√	-	√	√	-	√	-	-
3	1SE3	√	-	√	√	√	-	√	-	√	-	-
4	1SE4	√	-	√	√	√	-	√	-	√	√	-
5	1SE5	√	-	√	√	-	√	√	-	√	-	-
Smelting slags from Nundu 2												
6	2SE6	√	-	√	√	√	√	√	-	√	-	-
7	2SE7	√	-	√	√	-	-	√	-	√	-	√
8	2SE8	√	-	√	√	√	-	√	-	√	-	-
9	2SE9	√	√	√	√	-	-	√	√	√	-	-
10	2SE10	√	-	√	√	√	√	√	-	√	-	√

9.3.3.1 Fayalite crystals

All the samples from Msete 1 and Nundu 2 sites had fayalite crystals. The crystals are both relatively less blocky (Figure 9.14) than the fayalite (and monticellite) crystals of the Kalenga slags (see previous chapter), and less feathery compared to the fayalite crystals of Kigonsera slags (see Chapter 7). This, in terms of the cooling rate, means they cooled gently, neither too quickly nor too slowly. The fayalite crystals are pure, because 1 mol of SiO_2 combines with 2 mol of FeO (Bachmann 1982: 14; Anthony *et*

al. 1995a: 234; Table 9.12). Besides silica and iron, the crystals also contain minor amounts of magnesia, lime, manganese, titania, and alumina (see Table 9.12).

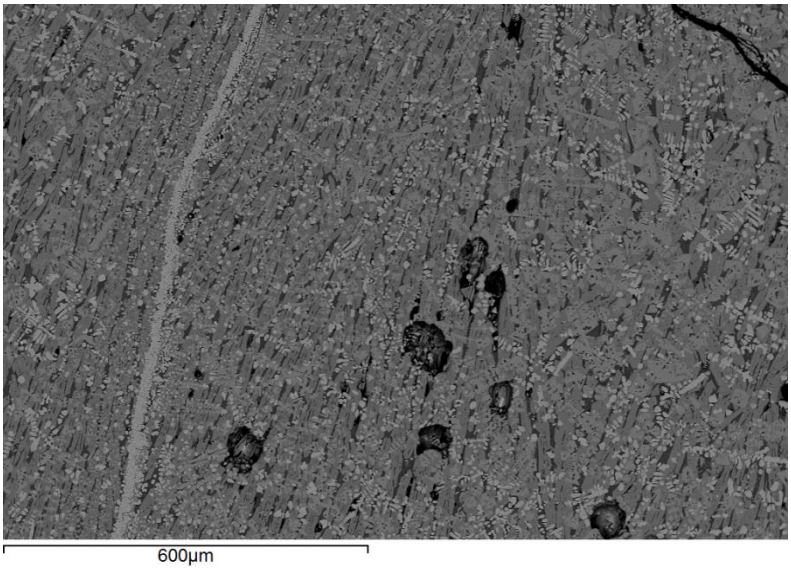

Figure 9.14: SEM-BSE image of fayalite microstructures of Msete 1 and Nundu 2 smelting slags (sample 1SE1). Note the tap line (white); small volume of glass in between the fayalite crystals; and porosity (black)

Table 9.12: SEM-EDS chemical composition of fayalite from the Msete 1 and Nundu 2 sites. Note the results are the average of three spectra and are normalised to 100 wt%; the full results in Appendix 9.6

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	CaO	TiO_2	MnO	FeO	Total
Smelting slags from Msete 1									
1	1SE1	1.3	0.3	30.6	0.8	0.7	0.7	65.6	100
2	1SE2	1.1	0.3	30.9	0.4	0.6	0.4	66.3	100
3	1SE3	1.3	0.1	30.6	1.0	0.4	0.6	65.9	100
4	1SE4	1.5	0.1	30.8	1.4	0.4	0.6	65.3	100
5	1SE5	1.9	0.3	30.8	0.9	0.5	0.5	65.0	100
Smelting slags from Nundu 2									
6	2SE6	1.1	0.1	30.7	0.5	0.4	0.6	66.6	100
7	2SE7	1.3	0.3	30.7	0.5	0.6	0.5	66.1	100
8	2SE8	2.4	0.3	31.0	0.8	0.5	0.6	64.4	100
9	2SE9	2.3	0.1	30.6	0.5	0.3	0.5	65.7	100
10	2SE10	1.9	0.1	31.1	0.6	0.5	0.5	65.3	100

9.3.3.2 Hercynite crystals

Only one sample from Nundu 2 site had hercynite crystals from this area (see Table 9.11). They are relatively small and secondary crystals, and are located around the ulvite spinels (Figure 9.15). Based on the ratio of 1:1 of FeO and Al_2O_3, they qualify as pure hercynite crystals, although there is relatively less alumina and more iron oxide in them (Anthony *et al*. 1997: 561). Other oxides in the crystals include titania about 4.5 wt%, and magnesia about 0.5 wt%.

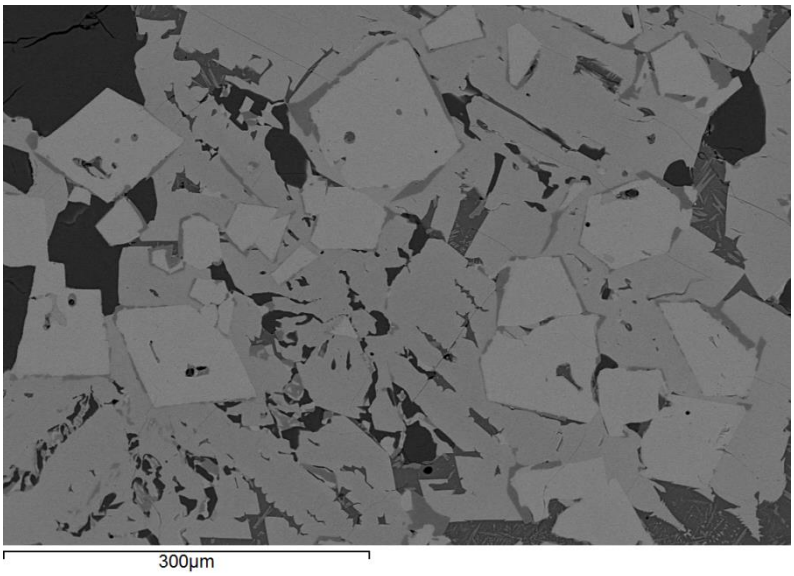

Figure 9.15: SEM-BSE image of hercynite microstructures of Nundu 2 smelting slag (sample 2SE9). The bright grey are ulvite spinels, grey crystals are fayalite, black are leucite crystals, and light black groundmass is glass

9.3.3.3 Glass groundmass

Glass acts as a background to all other crystals. The volume of the glass phase in these samples is describable as medium, not large or small (Figure 9.16). In principle, if slags cool very quickly they create large volumes of glass (see Kigonsera slags), and vice versa (see Kalenga slags). Based on this information, it is possible to think that the other slag crystals in this area cooled neither very quickly nor very slowly, but gently (for possible reasons for the proposed medium cooling of the slags, see tap lines section).

The major components of the groundmass are silica, iron, alumina, lime, potash, and titania (Table 9.13). The other minor components include phosphate, sulphide, and soda, all weighing less than 1 wt% on average (see Table 9.13).

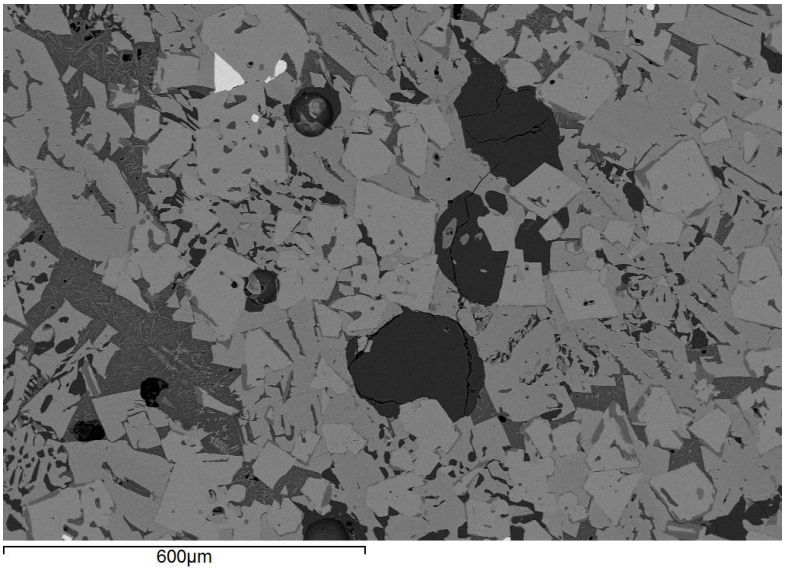

Figure 9.16: SEM-BSE image of the microstructures and medium volume of the glass phase (dark grey) in the slags from Njombe sites (sample 2SE9). The bright grey crystals are ulvite, grey are fayalite, black are leucite, white are iron particles, and light grey are hercynite.

Table 9.13: SEM-EDS chemical composition of glass groundmass from the Msete 1 and Nundu 2 sites. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	Na_2O	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	FeO	Total
Smelting slags from Msete 1											
1	1SE1	0.2	13.3	37.0	0.7	0.7	6.5	10.4	1.2	29.0	100
2	1SE2	0.3	15.8	39.0	0.6	0.5	7.0	11.4	1.2	23.0	100
3	1SE3	0.3	11.7	36.5	0.4	0.2	4.9	10.0	1.1	33.9	100
4	1SE4	0.5	15.4	38.2	0.7	0.5	5.9	13.8	1.3	22.9	100
5	1SE5	0.4	14.3	30.6	0.4	0.3	5.9	8.3	4.2	34.9	100
Smelting slags from Nundu 2											
6	2SE6	0.6	15.7	40.1	1.0	0.1	9.0	9.3	0.9	21.7	100
7	2SE7	0.4	14.9	37.6	0.9	0.3	6.2	11.6	1.4	25.4	100
8	2SE8	0.3	15.5	38.9	0.9	0.3	7.6	10.7	1.1	23.7	100
9	2SE9	0.4	17.1	48.0	0.7	0.2	4.3	11.2	1.1	15.9	100
10	2SE10	0.5	14.9	38.5	0.7	0.5	6.3	11.4	1.1	25.3	100

9.3.3.4 Ulvite crystals

All the slags contained ulvite spinels as one of the dominant phases. The crystals are relatively medium in size (Figure 9.17), and based on TiO_2.2FeO chemistry (Anthony *et al*. 1997: 582; Table 9.14), they are all pure ulvite spinels. Because there is relatively more iron oxide in the crystals, it might be thought that there would be extra iron oxide in the system chemically required to form the ulvite spinels. The dominance of this phase perfectly accords with the chemical data, and strongly supports the earlier proposition that the Bena people smelted Ti-rich magnetite ore. In addition to titania and iron oxide, on average, the ulvite crystals contained alumina, vanadia, magnesia, chromia, silica, and manganese as well.

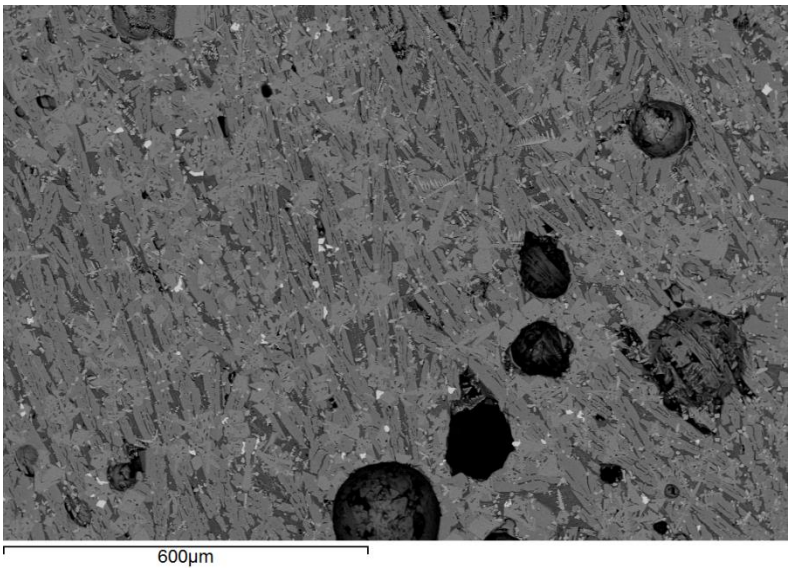

Figure 9.17: SEM-BSE image of the microstructures of ulvite spinels (angular white grey) in the slags from Msete 1 and Nundu 2 sites (sample 2SE7). The grey crystals are fayalite, black are porosity, white are iron particles, and dark grey is the glass phase

Table 9.14: SEM-EDS chemical composition of ulvite crystals from the Msete 1 and Nundu 2 sites. Note the results are the average of three spectra and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al_2O_3	SiO_2	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	Total
Smelting slags from Msete 1										
1	1SE1	0.5	7.4	0.5	22.5	3.1	0.3	0.2	65.1	100
2	1SE2	0.4	6.2	0.3	23.8	5.3	0.7	0.3	63.1	100
3	1SE3	0.4	5.6	0.4	24.7	3.9	0.3	0.2	64.3	100
4	1SE4	0.5	5.9	0.1	24.4	5.3	0.8	0.2	62.6	100
5	1SE5	0.6	7.9	0.3	22.6	2.5	0.1	0.2	65.9	100
Smelting slags from Nundu 2										
6	2SE6	0.5	8.5	0.2	20.8	5.1	0.6	0.2	64.0	100
7	2SE7	0.4	5.1	0.2	25.6	4.8	0.5	0.2	63.2	100
8	2SE8	0.8	7.4	0.2	23.7	5.0	0.7	0.4	61.8	100
9	2SE9	0.8	11.6	0.2	23.3	1.4	0.0	0.2	62.4	100
10	2SE10	0.5	7.7	0.2	21.8	6.5	1.3	0.1	61.9	100

9.3.3.5 Wüstite crystals

Of the 10 samples examined, 6 contained some secondary wüstite crystals (see Figure 9.17). The presence of little wüstite indicates that the Bena smelting process proficiently reduced most of the free iron oxides into a metal. To this end, among other things, they might have operated with optimum CO/CO_2 and fuel/ore ratios (Tylecote *et al*. 1971; Killick and Gordon 1989). Elsewhere in Southwestern Nigeria, the use of ilmenite ore was more beneficial for the reduction efficiency than the use of quartz as added material, because only one more mol of FeO is required to form ulvite, but the latter requires 2 mol of FeO to form fayalite (Ige and Rehren 2003: 20). Likewise, the use of ilmenite ores at Msete and Nundu sites decreased the amount of iron oxides wasted in the slags. In terms of chemical composition, on average, the wüstite crystals contained 93-95 wt% FeO, 3-4 wt% titania, 1-1.5 wt% each alumina and silica, and lime and vanadia about 0.2 wt% (Table 9.15).

Table 9.15: SEM-EDS chemical composition of wüstite crystals from the Msete 1 and Nundu 2 sites

S/No.	Sample/ Oxides	Al_2O_3	SiO_2	CaO	TiO_2	V_2O_5	FeO	Total
Smelting slags from Msete 1								
1	1SE1	1.2	0.8	0.2	3.6	0.3	94.0	100
2	1SE3	2.2	2.0	0.3	5.6	0.1	89.7	100
3	1SE4	1.2	1.6	0.5	2.6	0.1	94.0	100
Smelting slags from Nundu 2								
4	2SE6	0.6	0.6	0.1	2.3	0.5	95.9	100
5	2SE8	0.4	0.8	0.1	1.4	0.1	97.2	100
6	2SE10	1.8	0.7	0.1	4.4	0.4	92.7	100

9.3.3.6 Tap lines

Fifty percent of ten slag samples analysed from Njombe exhibited (relatively thick) tap lines (see Table 9.11) indicative of slag tapping practise. Compared to the tap lines of Kigonsera slags, for example, these tap lines are relatively thicker (Figure 9.18) suggesting that there was some time for the tap lines to grow larger, possibly because the melt cooled somewhat slowly (see the size of the earlier crystals). For this to happen, the smelters must have drained the slag into special, external slag pits outside the furnaces, where the slag cooled not too quickly or slowly. The shape of the blocky flow slags from both Msete and Nundu areas (see Figure 9.9) strongly supports this interpretation, because it appears that they were drained into deep pits. The oral evidence states that slag tapping was done via the *mlepulo* hole, but they were unclear how the liquid slag was handled outside the furnace.

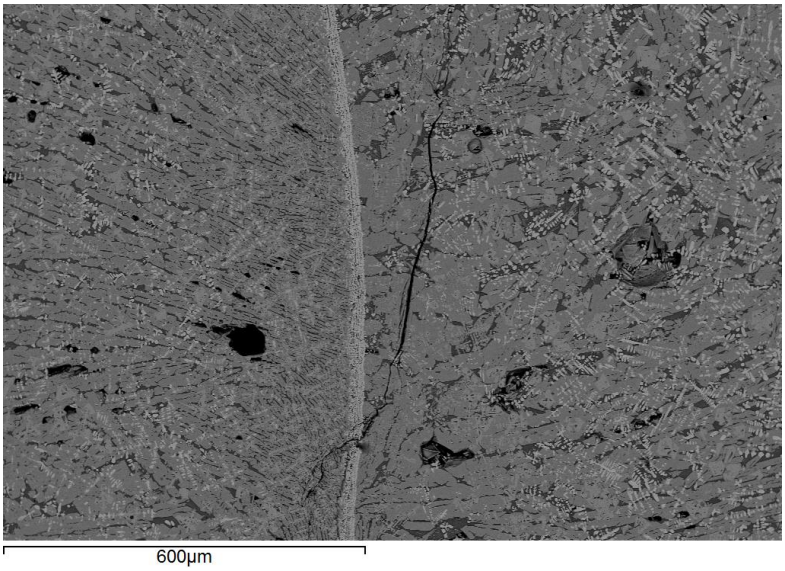

Figure 9.18: SEM-BSE image of (thick) tap lines in the smelting slags from Msete 1 and Nundu 2 sites (sample 2SE6). The grey crystals are fayalite, black are porosity, white grey are ulvite, white dendrites are wüstite, and dark grey is the glass phase

9.3.3.7 Iron particles

All the samples exhibited iron particles (see Table 9.11). The angularity of the particles (Figure 9.19; also see Figure 9.16) may be interpreted as suggesting that iron did not achieve a liquid state during the reduction process, in order, for example, to produce high carbon steel (see Chapters 5, 6, and 7). In addition, the presence of some wüstite strengthens the proposition that the Bena smelters perhaps did not achieve strongly reducing conditions in the furnaces to produce (high) carbon steels (see also, Ige and Rehren 2003: 20). Instead, one may argue, they were interested in producing (soft) iron or low carbon steels.

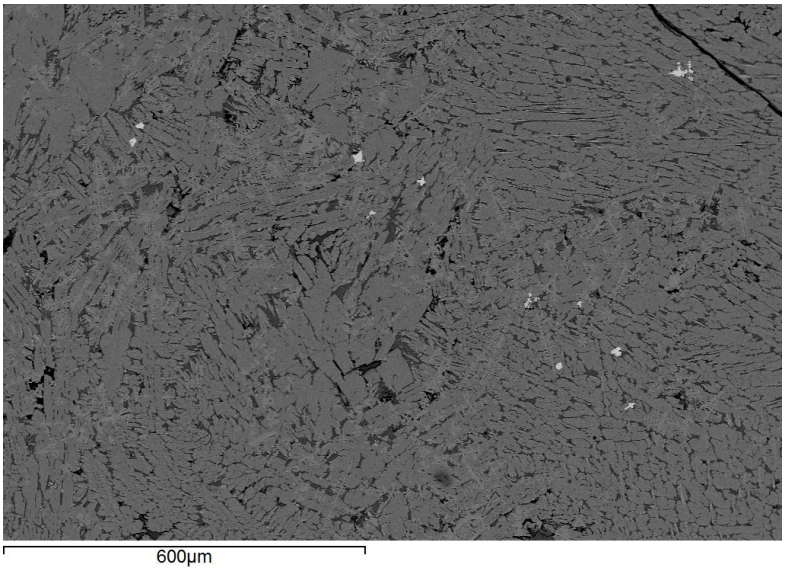

Figure 9.19: SEM-BSE image of the angular iron particles (white) in the smelting slags from Msete 1 and Nundu 2 sites (sample 1SE2). The grey crystals are fayalite, black are porosity, white grey are ulvite, and dark grey is the glass phase

9.3.3.8 Leucite crystals

Only one sample (2SE9) from Nundu had medium-sized leucite ($K_2O.Al_2O_3.2SiO_2$) crystals (see Figure 9.16 above). In terms of chemical composition, they are concentrated with silica about 55 wt%, alumina about 22 wt%, potash about 21 wt%, and FeO about 2 wt%. Based on the chemical data, the crystals are pure, because potash, alumina, and silica are combined to the ratio of 1:1:2 respectively (Anthony *et al*. 1995b: 462).

9.3.3.9 Porosity and quartz crystals

While all the samples were porous, the porosity was unevenly concentrated across the samples. On the other hand, only 1 sample (1SE4) was concentrated with quartz crystals (Figure 9.20). Assuming that the slag cooled in pits relatively slowly (for details on this, see fayalite, and tap lines subsections), there is no reason to think that the cracks of the

quartz crystals were due to thermal shock of the rapid cooling of the slag. Instead, the cracks were possibly initiated due to high temperatures in the furnaces.

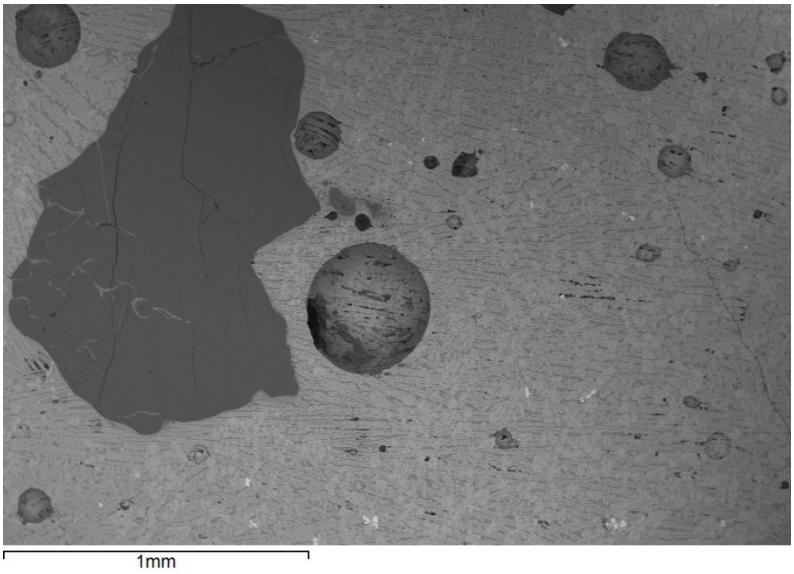

Figure 9.20: SEM-BSE image of (cracked) quartz particles (centre) in the smelting slags from Msete 1 site (sample 1SE4). The grey crystals are fayalite, black are porosity, white grey are ulvite, and white are iron particles

9.3.3.10 Other crystals

Two samples from Nundu 2 site (see Table 9.11) had secondary (or tertiary) spinels noticeable at high magnification, 2500 and 4000 respectively. In terms of chemical composition, they contain about 86 wt% FeO, 6.5 wt% titania, 4 wt% alumina, 3 wt% silica, and less than 1 wt% lime. One hypothesis is that they are magnetite crystals that possibly formed due to the re-oxidation of the ulvite spinels during the slag tapping process, because they are confined to the end of the samples (Figure 9.21). The other possibility is that they could be ore fragments accidentally incorporated at the end of the smelting episode. Whatever the case, they cannot be classified precisely, and, are possibly less representative of the actual smelting conditions.

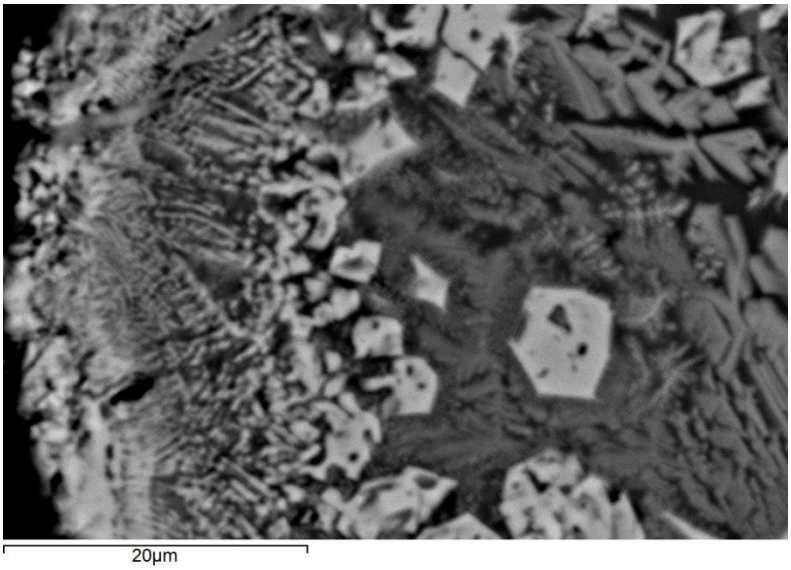

Figure 9.21: SEM-BSE image of magnetite-like or oxidized-ulvite crystals (angular white) in the smelting slags from Nundu 2 site (sample 2SE7). The grey crystals are fayalite, and black is the glass phase

9.4 Discussion of the Aims of the Chapter

The aims of this chapter were presented earlier in Chapter 2 (see Previous Archaeological Knowledge in Njombe). The five aims include:

(1) examining the nature of the technical ceramics,

(2) finding out how Bena smelting furnaces were operated in terms of an air supply mechanism,

(3) investigating how liquid slag was handled during the smelting process

(4) examining the efficiency of iron reduction and its associated factors, and

(5) discussing the nature of the final smelting product of the Bena metal production process. In this section, the aims are revisited and discussed, based on the macroscopic and microscopic data presented above.

First on the nature of the raw materials used to construct and manufacture iron smelting furnaces, tuyères, and pottery. The (slight) variation in the chemical data of the tuyères and pottery (see Figure 9.12) suggests that perhaps the sets of ceramics were collected

from related but different sources of clay. Because the furnace samples from Nundu 2 are somewhat different from those of the tuyères and pottery, it can be argued that the three sets of technical ceramics were clearly sourced from different clays. Like the Hehe, the smelters selected the highly refractory clays for the manufacturing of thermal shock resistant tuyères, while the clays for the construction of the furnaces were comparatively medium refractory, and yet the clays for the pottery had the lowest maximum refractory quality (see Figure 9.12). The tuyères were relatively subjected to the highest temperatures inside the furnace, and appropriately they were supposed to be more thermal shock resistant than the furnace walls (see Freestone and Tite 1986; Childs 1989a). By and large, the success in giving due weight to these technical requirements and distinctions within the refractory quality, was arguably critically significant to the endeavour and practice of effecting successful smelts, and indeed, reflected the skills of the smelters (see also Freestone and Tite 1986: 36; Freestone 1989).

Second: on the air supply mechanism. While no flared or trumpeted tuyères often indicative of forced draft mechanisms (see Mapunda 2010: 126; Childs 1996: 286) have been recovered, yet there are strong reasons to claim that the smelting furnaces were operated by bellows. (1) The size of the furnaces (especially their internal diameter of 30-32 cm) is relatively small for a natural draft operation. For example, natural draft smelting furnaces of Mbozi had an average (base) internal diameter of about 160 cm (see Chapter 7). (2) The Bena furnaces have three tuyère ports, while elsewhere in Central and Eastern Africa (q.v. van der Merwe and Avery 1987; Killick 1990; Barndon 2004; Mapunda 2010) natural draft furnaces commonly have at least 6 tuyère ports depending on the size of the furnaces. In Unyiha, for example; each of the 9-10 slits housed multiple tuyères of relatively small internal diameters of about 3 cm; by contrast

the Bena furnaces housed 1 single tuyère with an internal diameter of about 4 cm. And (3), the height of about 1 m for the Bena furnaces is unconventional for natural draft furnaces, because van der Merwe and Avery (1987: 149) have convincingly argued that a height of at least 1.5 m works better for natural draft furnaces. As well as the measurements and observational data, literature data (e.g. Mapunda 2010: 68) and oral evidence (see Appendix 4.2e) have categorically asserted that the Bena used bellows to supply air to the smelting furnaces.

Third: on handling out of the liquid slag. In the field, the lack of (relatively deep) furnace slag-pit provision, a substantial number of droplet slags, and the presence of a large number of flow slags all signalled the slag tapping practice in Ubena. Unfortunately these macroscopic evidences alone are inconclusive without microscopic data, because flow slags could be produced in furnace slag pits as well (see Haaland and Msuya 2000: 81; Haaland 2005: 190-195). Microscopically, while fayalite and ulvite crystals are relatively so (medium) blocky that it would be impossible without the aid of tap lines to tell with precision that these were tapped samples. Although we conventionally accept that tap slags cooled rapidly, the Bena case was slightly different. The tap lines (see Figure 9.15; Figure 9.18) are relatively thicker than the Kigonsera tap lines (see Chapter 7) indicative of relatively medium cooling as opposed to the slow cooled slags of Uhehe (see previous Chapter). One possible explanation is that while tapping the slag was perhaps drained into deep pits (outside the furnace) where it cooled relatively slowly (albeit not too slowly). The shape of the blocky slags with conspicuous flows (see Figure 9.9) further supports the idea that they were tapped or drained into pits. This explains why the crystals were not too large and not too small, and this find is uncommon in Tanzania. Lastly, the paucity of slags at these sites also supports the current interpretation for they might have been buried in the pits.

Fourth: on the reduction efficiency of the Bena iron-smelting process. On average, there was about 59 wt% FeO concentration in the slags, but the figure includes even chemically-bound atoms of iron in the fayalite and ulvite crystals, for example. By implication, the more such crystals are concentrated in the slags (assuming other free iron oxides are kept constant) the figure is likely to increase, from 59 wt% upwards. Relying on the FeO chemical data alone, therefore, is likely to mislead the examination of reduction efficiency, let alone the fact that chemically-bound atoms of Fe in non-free iron oxides were probably impossible to reduce to iron metal in iron metallurgy. Being aware of this problem, it is conventional to use free iron oxides, especially wüstite, while discussing the efficiency of the iron reduction process (e.g. Morton and Wingrove 1969, 1972; Bachmann 1982; Childs 1996; Chirikure 2006; Mapunda 2010). On the basis of little (secondary) wüstite in some of the slags of Msete and Nundu sites, it is correct to posit that the Bena iron smelters were technically efficient. Compared to some iron smelters in southern Tanzania, the Bena were more technically efficient than the Hehe (see previous Chapter), but they were less efficient than the Matengo of Kigonsera (see Chapter 7).

In terms of the responsible factors, an effective fuel to ore ratio, say, of about 1:1, would have ensured optimal reduction of iron and reduced loss of free (primary) iron oxides into the slags (see Tylecote *et al*. 1971: 352). In addition, the use of relatively massive tuyères with large internal diameters ensured enough air supply to the smelting furnace, and standardized, optimal blowing rates (e.g. Klapwijk 1986a; Gordon and Killick 1993; Chirikure 2006), optimal CO/CO_2 ratio (e.g. Killick and Gordon 1989) were hopefully approached. The use of titanium-rich ore indicated by ulvite spinels more likely increased the yield as well, because only 1 atom of iron of the (ilmenite) ore was wasted in the slags in the form of the ulvite crystals, instead of 2 atoms of iron to be

wasted in the slags due to the formation of fayalite crystals (see Ige and Rehren 2003: 20). Besides the observable factors, better skills and experience of the smelters, labour (e.g. travelling one day to collect *mdapu* ores, chopping and burning charcoal, medicinal ingredients preparation, etc.) and time aspects were significant contributory factors.

Lastly: on the nature of the final product. Depending on the skills, preference or prospective use of the final product, smelters might produce either iron or steel. Conventionally, to produce the former, one needs relatively modest enough reducing conditions, while to produce the latter requires highly reducing conditions in the furnaces (see Tylecote *et al*. 1971; Bachmann 1982; Rehren *et al*. 2007). Other factors being kept constant, high fuel to ore ratio and maintenance of high air supply and temperatures in the furnaces, among other factors, are likely to produce steel (e.g. Tylecote *et al*. 1971: 352). In terms of slag exhibits, more free iron oxides in the slags indicate relatively less efficient reducing conditions in the furnace, and vice versa (e.g. Killick 2004a; Mapunda 2010). The presence of some wüstite in the slags of this area indicates enforcement of relatively less (?) or medium reducing conditions in the furnaces, which make it more likely that the smelters aimed at and produced soft iron and not high carbon steel as with the Matengo of Kigonsera (see Chapter 8). This proposition is further strengthened by the angularity of the iron particles in the slags (see Figure 9.16; Figure 9.17; Figure 9.19), because highly reducing conditions of a steel (or cast iron) process will often make its iron prills inclusions perfectly round/ circles (see Chapter 8; Tholander 1989: 38). Nevertheless and compared to the Hehe process (previous Chapter), the Bena process yielded more iron, possibly with little carbon as well.

9.5 Summary

The main objective of the chapter was to examine spatial variation of iron production in Njombe (see preamble section). Based on the macroscopic and microscopic data discussed above, I can sum up that Msete and Nundu smelters practised similar iron production technology especially in the use of Ti-rich mdapu ores; use of fairly refractory clays; tuyères being more refractory than furnaces; and pottery were the least refractory clays, and use of a forced air draft mechanism. Also, they both practised slag tapping by draining the slag into a pit outside the furnace, reached similar chemical and mineralogical reduction efficiency possibly due to similar factors, and produced soft iron as the final product of the smelting process. What follows is the overall discussion chapter for this work.

10. Discussion: Explaining the Research Objectives

10.1 Preamble

In the introductory chapter, six specific research objectives for this work were presented. To recap, they are (1) examining the nature of the technical ceramics, (2) finding out how the iron and steel production furnaces were operated, especially in terms of air supply mechanism, (3) investigating the possible presence of a three stage (smelting-refining-smithing) process of iron and steel production, (4) examining how (hot) liquid slag was handled during the iron and steel production process, (5) evaluating iron and steel production efficiency and associated factors, and (6) discussing the nature of the final products of the smelting and refining processes. Here I revisit and discuss the objectives in light of the macroscopic and microscopic data (see Chapters 5-9) as well as other published data on these topics. For the purpose of clarity, I discuss each of the objectives separately. A summary of the chapter is provided at the end.

10.2 Nature of the Technical Ceramics

Here the claims of termite mounds as clay sources for the construction and manufacturing of *malungu* and *vintengwe* furnaces and tuyères (e.g. Killick 1990; Barndon 2004; Mapunda 2010) are examined using archaeological and experimental samples from Ufipa and Unyiha. The possibility that working place (WP) depressions of the Kalenga sites were used as clay sources for the furnace rolls and tuyères is also examined. The question whether or not iron and steel producers were clay-selective for different technical purposes (*cf.* Freestone and Tite 1986) is evaluated as well. To start with, and based on the chemical data (see Chapter 5, on technical ceramics), the furnace

and tuyère samples from Mkumbi smelting site #3, and the furnace and tuyère samples from Mkumbi refining site #2 are chemically similar, indicative of similar clay sources. Because the two sets of technical ceramics are each chemically similar to the test briquettes (TBs) from nearby termite mounds, and although there is a relatively higher silica concentration in the TBs, it is safe to suggest that the two termite mounds nearby the sites were used as the clay sources for the technical ceramics. The relatively higher concentration of silica in the TBs is due to possible differences in the sampling methods of the archaeological (furnaces and tuyères) and experimental (TBs) samples, and therefore, I propose this be disregarded. The chemical similarity of the two sets of technical ceramics and TBs is further strengthened by a similarity in their refractory quality (see Chapter 5, on technical ceramics; for similar findings elsewhere in Kenya, see also Iles 2006: 40; Iles and Martinón-Torres 2009: 2318). The use of nearby termite mounds as sources of clay for the production of furnaces and tuyères extends to other sites in Ufipa including Mkumbi smelting site #4 and refining site #5B, although the iron and steel producers shared the termite mound located between the two sites (see Chapter 5, technical ceramics section), and in Unyiha including Itaka smelting site #1 and refining site #2, although the furnace and tuyère samples from Itaka refining site #2 might have come from separate termite mounds (see Chapter 6, technical ceramics section). Based on the findings, it is clear that iron and steel producers selected termite mounds, because the clay from them had good refractory quality of up to 1650 ^{o}C on average. This refractory quality was good enough for the conventional iron and steel production temperature of about 1200 ^{o}C (e.g. Childs 1989a; Humphris 2010). There was no technical need for the metal producers to look for other clay sources to produce tuyères with higher refractory quality than the furnaces (*cf*. Freestone and Tite 1986;

Childs 1989a), because the termite mound clays were adequate for this purpose (for similar results elsewhere, see Iles 2006: 40, 2011: 149; MacDonald *et al*. 2009).

Similarly, the chemical data of the TBs (sampled from WPs) and furnace rolls from the Kalenga smelting sites have indicated that the two sets are chemically similar, although there are relatively higher silica and soda concentrations in the TBs (see Chapter 8, technical ceramics section). The relatively higher silica concentration in the TBs was due to possible differences in the sampling and preparation methods for the two sets of samples. This diluted and lowered the concentration of the other oxides in the TBs. If I ignore the little chemical mismatch, which is often difficult to triumph over even with archaeological samples (see Severin *et al*. 2011; Lyaya *et al*. 2012), it is likely that the WPs depressions at the Kalenga smelting sites were utilised as sources of clay for the production of the furnace-clay rolls. However, as opposed to the termite mounds of Ufipa and Unyiha discussed above, the WPs in Uhehe did provide furnace clay rolls alone, because the furnace-clay rolls are chemically very different from the tuyère and pottery samples (see technical ceramics data on Ngongwa site #1). Interestingly, it seems that the clay for the manufacturing of the tuyères and pottery came from separate sources as well, because the two sets of samples are also chemically dissimilar (see Chapter 8, on technical ceramics). Furthermore, the chemical differences between the clay rolls, tuyères, and pottery at Magubike sites #1 and #2 (see Chapter 8, technical ceramics section) generally indicate that there was probably an intentional selection of different clays for different technical ceramics (see Freestone and Tite 1986; Childs 1989a; Schmidt 1997a). Apart from Kalenga, iron and steel producers in Njombe and Mbinga also selected different but fairly refractory clay sources for the construction and manufacturing of the technical ceramics. The clay source for the tuyères in Njombe was however the same for the three sites (see Chapter 9, technical ceramics), suggesting

some sort of control of the clay sources, assuming that the Nundu and Msete smelting furnaces were controlled by different chief smelters. In Mbinga, the smelters selected different clays for the manufacturing of possible furnace platforms, furnaces, tuyères, and pottery (see Chapter 8, on technical ceramics). In sum, iron and steel producers selected largely refractory clays to produce the technical ceramics for successful smelts (see Freestone 1989: 156), which reflects their high level of skills (see Freestone and Tite 1986: 36). It is noteworthy that although the technical ceramics examined here were capable of withstanding high temperatures of up to 1700 ^{o}C, the iron and steel technical ceramics only needed to have a refractory quality of 1200-1300 ^{o}C. It is equally important to note that although all the technical ceramics had good refractory qualities, it seems that the tuyères, wherever different sources of clay were in use, were overall *dimensionally* more stable than others, because they were richer in quartz (see Freestone and Tite 1986; Tite *et al*. 2001), and that smelting and refining furnaces were generally more refractory than pottery and platforms.

10.3 Furnace Air Supply Mechanisms

The shape of the proximal end of a tuyère is a good indicator of the nature of air supply mechanism into iron and steel furnaces (e.g. Childs 1996; Schmidt 2006; Mapunda 2010; Humphris 2010; Iles 2011). It is known that flared or trumpeted proximal ends are associated with a forced draft mechanism for smelting furnaces, because they provided receptacles for bellows (for examples, see Mapunda 2010: 126; Humphris 2010: 40; Iles 2011: 142). Flared tuyère proximal ends were recovered from smelting sites in Umatengo and Uhehe (see Chapters 7 and 8; and Figure 10.1) indicating that they were perhaps employed in forced draft furnaces. This interpretation is also supported by ethnographic evidence (for example, see Kapinga 1990). Although no flared tuyère proximal ends were discovered from the Ubena smelting sites, probably

because most of the smelting debris in this area are buried (for details, see Chapter 9), one may be confident, based on oral evidence, that the iron smelting furnaces were operated by a forced draft mechanism (see also Lyaya 2011). In addition, the relatively small size and presence of less than 4 tuyère ports for the iron and steel smelting furnaces from Umatengo, Uhehe, and Ubena (see Chapters 7-9) are consistent with forced draft furnaces (van der Merwe and Avery 1987: 149; see also Holl 2009: 423). As such, the forced draft smelting furnaces of this region are comparable to the forced draft smelting furnaces of the Haya (e.g. Schmidt and Avery 1978; Childs 1996), Rongo (e.g. De Rosemond 1943; Schmidt 1996), and the Pangwa (e.g. Barndon 2004; Schmidt 2006) all in Tanzania.

Figure 10.1: Flared tuyères from Umatengo

On the other hand, non-flared tuyère proximal ends, that is, tuyères with uniform diameter from tip to tip (Figure 10.2), have been found from smelting and refining sites in Ufipa and Unyiha (see Chapters 5 & 6). There is sufficient ethnographic evidence that iron smelting furnaces in these societies operated by natural draft mechanisms, and

that the (*vintengwe*) refining furnaces operated by bellows (see Greig 1937: 79; Wise 1958: 110; Brock and Brock 1969: 98). There is no doubt that the large size, height, and presence of *circa* 10 tuyère ports for the smelting furnaces in Ufipa and Unyiha (see Chapters 5 & 6) support the use of a natural draft mechanism (see van der Merwe and Avery 1987; Holl 2009). Likewise the small size and short height of the refining furnaces would support the use of bellows (for a critique of Mapunda's (2010) association of unflared tuyère ends with forced natural draft furnaces, see below). Iron smelting at Ntuha site perhaps employed natural draft furnaces, because no flared tuyère proximal ends were recovered, the furnaces were possibly tall enough to require charging platforms (see Chapter 7, on furnace attributes), and the furnaces may have had nine tuyère ports according to Mapunda (1991). Natural draft furnaces have been identified elsewhere in Zambia (e.g. Chaplin 1961), Zimbabwe (e.g. Chirikure and Rehren 2006), and Nigeria (e.g. Ige and Rehren; Whiteman and Okafor 2003).

Figure 10.2: Unflared tuyère proximal ends from Ufipa

Based on the interpretations above, several propositions can be raised in relation to the question of air supply mechanism in archaeology. First, the association of the shape of the tuyère proximal ends with the nature of furnace air supply mechanisms alone (e.g. Mapunda 2010: 126) is inconclusive to explain the air supply mechanism for the iron refining furnaces, although it has worked for the smelting furnaces of the region. Second, the association of internally oxidised tuyères with natural draft furnaces alone (see Chirikure and Rehren 2006: 50) is inadequate, because there are internally unoxidised tuyère pieces in the natural draft furnaces in Ufipa. According to the oral evidence, these were placed inside the furnace at each port and perpendicular to the ordinary tuyères to support the ordinary tuyères projecting inwards (Figure 10.3; see also Haaland *et al*. 2002: 45; Mapunda 2010: 154). Third and last, the use of multiple tuyères should not be restricted to natural draft furnaces alone as Killick (1991: 63) claims, because the (later) forced draft smelting furnaces in Umatengo employed multiple (3-4) tuyères per port that were arranged horizontally, one next to each other (see also Kapinga 1990) as opposed to the conventional one on top of the other tuyère arrangements in Ufipa and Unyiha (see Barndon 2004; Mapunda 2010). The multiple tuyères in Umatengo were not used for slag tapping as in Ufipa and Unyiha (see slag handling below). Therefore, in order to suggest the nature of air supply mechanism, it can be argued, one needs to consider several factors including ethnographic and archaeological data such as tuyère proximal end shape for the smelting furnaces, size and height of the furnaces, and the number of tuyère ports per furnaces.

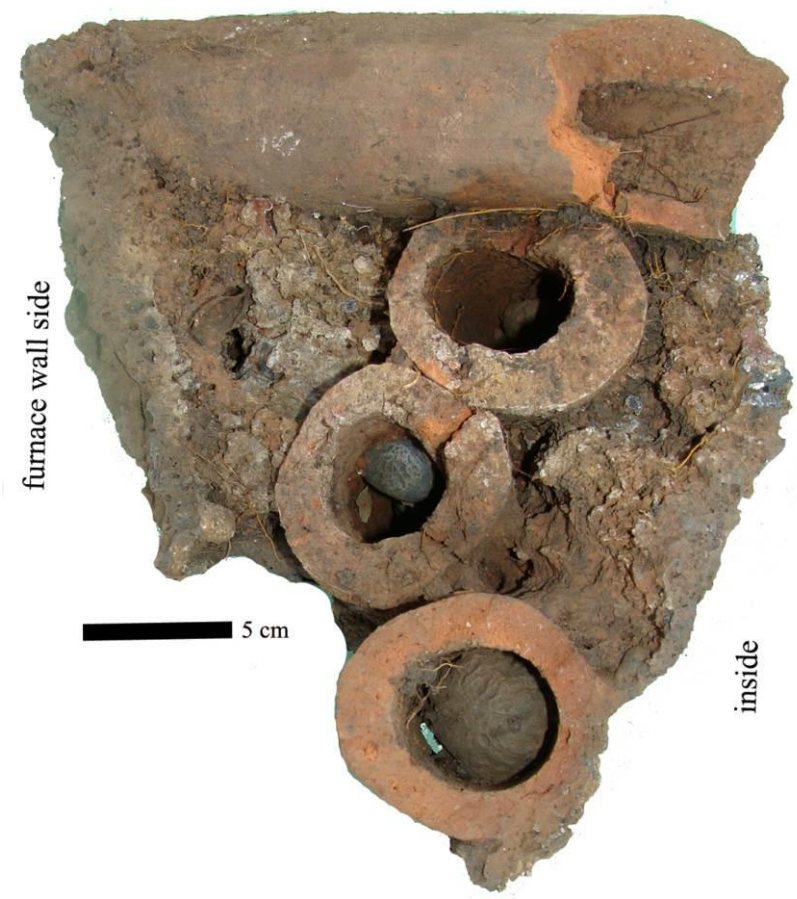

Figure 10.3: Three internally unoxidised tuyères (one on top of the other) from natural draft furnaces in Ufipa

10.4 Presence of a Three Stage Process of Iron and Steel Production

Here three lines of evidence including: (1) field or macroscopic evidence, (2) chemical data, and (3) mineralogical data are discussed to demonstrate the presence of a three stage (smelting-refining-smithing) process of iron and steel production in southern Tanzania, especially in Ufipa and Unyiha. Macroscopically, and based on the data presented in Chapters 5 and 6, the smelting process can be differentiated from the refining process at three different levels including: (1) location or spatial organisation of the sites, (2) size of the sites, and (3) material composition of the sites. First, and in terms of the location, smelting sites of Ufipa and Unyiha are *always* situated next to, and on the *western* side of, termite mounds, mainly for social-cultural reasons (see

Mapunda 2010: 156-8; elsewhere see Maluma 1979; Fagan 1962), but the refining sites were located *anywhere* but always on sloping ground for draining the slag via a tunnel (see Wise 1958: 110). Contrary to the smelting and refining often being secluded from the general public, the smithing process was often conducted in or near settlements (see Greig 1937). Second, the smelting sites are generally larger in size (and debris volume) than the refining sites. On average, the smelting sites in Ufipa are about 330 m^2, while the refining sites are about 220 m^2 in area sizes (see Chapters 5 & 6). The difference in size is more likely to be related to the differences in the size and bulk (raw) materials charged into the *malungu* and *vintengwe* furnaces respectively. For similar reasons, it is no surprise that the smithing sites from Ufipa and Unyiha were only *circa* 50 m^2, on average, in area size (see Chapters 5 & 6). Third and last, the material composition of the processes is also different: (1) the tuyère mould slags and frequent multiple tuyères in Ufipa and Unyiha are exclusive features of the smelting sites, because of the differences in the slag tapping methods and the number of tuyères per port between the two processes (for the details, see air supply mechanism above, and liquid slag handling techniques below), and (2) the refining sites largely about 99 % consist of small (smooth) flow slags, while the smelting sites comprise about half (smooth) flow slags and half (rough) blocky slags (see Chapters 5 & 6). The remaining 1 % of the refining site materials includes cake-like slags, tuyères, and occasional rejects of iron ('bloom') pieces. On the other hand, smithing sites in these areas are exclusively composed of (hammer) scales, droplets, agglomerated, and smithing hearth bottom (SHB) slags as well as tuyères. In sum, our macroscopic data support Mapunda's (2010: 154) proposal, that the *malungu* and *vintengwe* processes can *clearly* be distinguished in the field.

Chemically, the smelting slags can be differentiated from the refining slags in terms of FeO concentration. There is a systematic increase in FeO concentration in the refining

slags (see Chapters 5 & 6, on the slag chemical data). On average, the smelting slags from Ufipa and Unyiha had FeO concentration about 43 and 32 wt% respectively, while the refining slags had FeO about 52 and 41 wt% respectively (see Chapters 5 & 6, on the slag chemical data). The increase in FeO concentration was possibly due to iron contamination in the refining slags in terms of the iron droplets (see Chapters 5 & 6, on slag mineralogical data). It is often difficult to fully avoid iron loss in the slags, especially when the slag is close or in contact with the iron, steel, or cast iron (e.g. Killick and Gordon 1987; Rehren and Ganzelewski 1995; Miller and Killick 2004; Chirikure 2006: 151). As would be expected, the increase in FeO concentration in the refining slags systematically lowered the concentration of others including silica, manganese, potash, lime, magnesia, and phosphate (see Chapters 5 & 6). Although both smelting and refining slags plot into the Optimum efficiency zone 1 (see Rehren *et al*. 2007) on the Al_2O_3-SiO_2-FeO diagram, the chemical difference between the two is visually obvious (see Chapters 5 & 6), because the smelting slags plot on the top side and the refining slags cluster at the bottom side of the Optimum efficient zone 1. These production stages (smelting and refining), however, are different from the *third* smithing process, because smithing slags are richer in iron oxide(s) (see Miller and Killick 2004: 26).

The smelting slags are also mineralogically distinguishable from the refining slags in two major ways. First, there are glimpses of wüstite in the smelting slags (for similar results of the presence of wüstite in the smelting (*malungu*) slags, see also Mapunda 2010: 175), while the refining slags have no wüstite, although one refining polished slag sample from each Ufipa and Unyiha had negligible wüstite. The presence of wüstite in the smelting slags is indicative of the need of the *second* (refining) stage to complete the reduction process of the wüstite in the smelted impure iron. It is noteworthy, however,

that the presence of some wüstite in the smelting slags indicates that the smelted product was possibly forgeable (see Wise 1958: 110; Brock and Brock 1965: 98). In the words of Wise (1958: 110), for example, the smelted iron was sufficient to make axes and small hoes for women. Second, while there are no iron droplets in the smelting slags from Ufipa and Unyiha, all the refining slags from the two areas systematically contain iron droplets (see Chapters 5 & 6, on slag mineralogical data). In addition to the need to reduce wüstite by 100 %, the presence of the iron droplets in the refining slags indicates not only that the smelters and refiners achieved their complete reduction goal, but also that they wanted to carburise the iron, which they succeeded in doing (see Chapters 5 & 6, on slag mineralogical data). The carburisation process was not accidental; because each and every randomly selected refining slag in Ufipa and Unyiha showed the iron droplets (see Chapters 5 & 6). It is important, however, to bear in mind that (African) smithing processes conducted largely on open fires more likely decarburised the carbon rich steels to low carbon steels (see van der Merwe 1980; van der Merwe and Avery 1982; Mapunda 2010). This means, the first smelting stage perhaps produced iron, the second refining stage produced high carbon steel, and the third smithing stage produced low carbon steel (for more details, see discussion of the final products). My findings demonstrate the presence of a three stage iron and steel production process, and they support what Wembah-Rashid (1969: 66) wrote that "*exactly* there are three stages: the kiln [smelting] stage, the blast furnace [refining] stage, and the smithing stage".

10.5 Liquid Slag Handling Techniques

Here the main purpose was to find out how the liquid (hot) slag was tapped and cooled during iron and steel production. Macroscopically, slag tapping is indicated by (1) the presence of large quantities of flow slags (see also Mapunda 2010), (2) the absence or

paucity of droplet slags (e.g. Schmidt and Childs 1985: 56), (3) the presence of tuyère mould slags (see Barndon 2004; Mapunda 2010), and (4) the lack of slag-pit provisions (see Schmidt and Childs 1985) in case of available furnace remnants (see Chapters 5-9). It is noted, however, that flow slags or slags with flow marks or lines can result from a non-slag tapping process as well (see Haaland and Msuya 2000: 81; Chirikure 2006: 148). In addition, slag tapping via funnel-shaped channels or tunnels dug down the slope (see Wise 1958: 110) does not produce tuyère mould slags. To rectify this problem, macroscopic evidence for slag tapping should be tested by microscopic examination, especially of the slags. Microscopically, slag tapping is indicated by the presence of (clear) magnetite skins or tapping lines, and the thin and elongated crystals of slag minerals such as fayalite, ulvite, and wüstite (see also Chirikure and Rehren 2006: 43). Based on the macro- and microscopic data (see Chapters 5-9), iron and steel production in the southern highlands of Tanzania involved slag tapping and non-slag tapping processes. The former category included the (later) Fipa, Nyiha, Matengo, and Bena iron and steel smelting processes, and (later) iron refining processes in Ufipa and Unyiha, while the latter included the (early) iron production in (Ntuha) Umatengo as well as the (early and later) iron production in (Kalenga) Uhehe. Slag tapping in Ufipa and Unyiha was done through the tuyères indicated by the presence of tuyère mould slags in large quantities (Figure 10.4; see also Mapunda 2010: 73). The absence of the tuyère mould slags from the smelting sites in (Kigonsera) Umatengo and (Njombe) Ubena suggests that slag tapping was not done through tuyères, instead, the slag was tapped perhaps through holes made at the base of the furnaces (for example a *mlepulo* hole in Ubena, see Chapter 9). For the iron refining furnaces in Ufipa and Unyiha, it strongly appears that slag tapping was done through a channel, as Wise (1958: 110) had observed that "the blast [refining] furnace was built on a sloping site, and that in front of

the furnace, a small funnel-shaped channel was dug to allow the slag to run away". The (medium) size of the slag crystals from Ubena indicates that the slags did not cool rapidly as typical for a tapped slag (e.g. Chirikure and Rehren 2006: 43). One possible explanation is that when the slag was being tapped outside the furnaces, it was channelled directly to *special* slag collection pit(s) where it cooled not too slowly or rapidly (Figure 10.5; for similar practises elsewhere in Taruga and Samum Dikuya, see Holl 2009: 417). An inquiry into why the slag could have been buried was not productive, but I strongly believe (by intuition) that it was for safety reasons, in order to avoid the risk of being burnt by (hot) liquid slag, or it could have been due to the iron-child (re)production symbolism. Apart from that, the smelting and refining tap slags from Ufipa, Unyiha, and Umatengo cooled quickly in the ambient air, because they have thin and elongated microstructures (Figure 10.6). The results on the slag tapping techniques are reliable, because elsewhere on the African continent, slag tapping processes have been identified, for example; in northern Zimbabwe (see Chirikure and Rehren 2006), northern Rhodesia (now Zambia) (see Chaplin 1961), and in southern Nigeria (see Ige and Rehren 2003).

Figure 10.4: Smelting tuyère mould slags from Ufipa

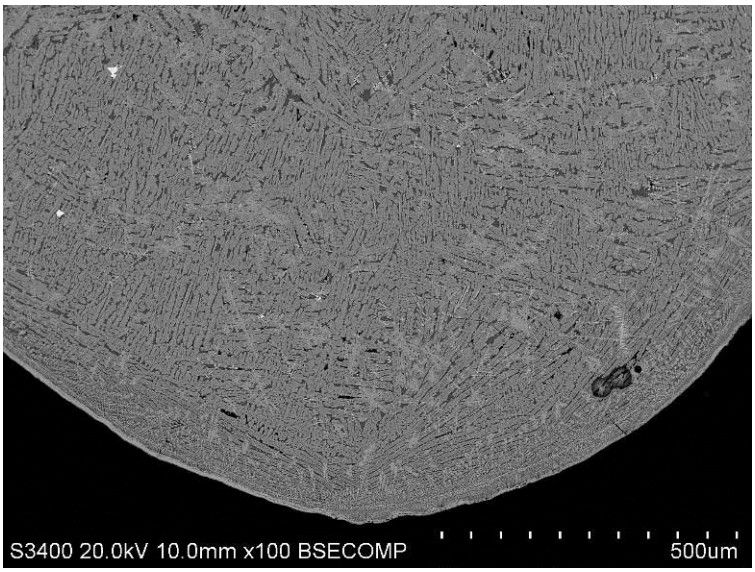

Figure 10.5: Microstructures of a medium cooled tap slag from Ubena. Note tap line (white), angular iron (white), fayalite (grey), wüstite (white grey), glass (dark grey), and porosity (black)

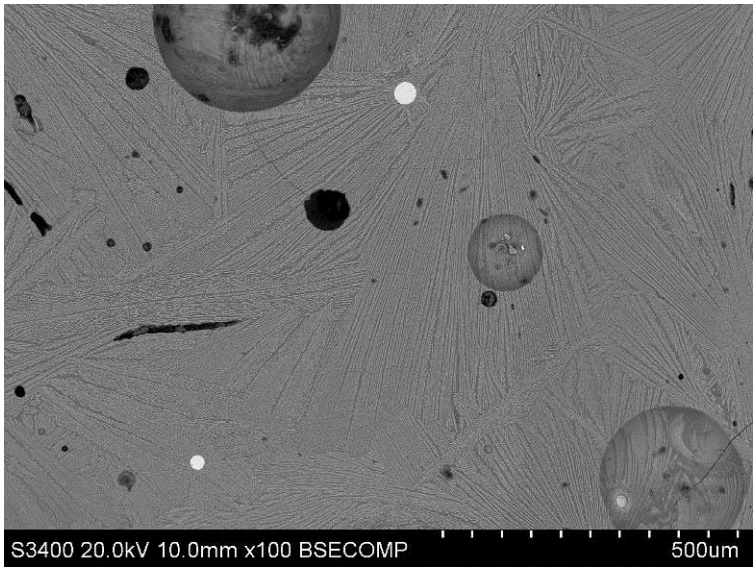

Figure 10.6: Microstructures of a rapidly cooled (refining) tap slag from Unyiha. Note droplets of iron steel (white), thin and elongated fayalite (grey), glass (dark grey), and porosity (black)

On the other hand, the (early) Ntuha iron smelting and (early and later) Kalenga iron smelting processes employed non-slag tapping furnaces, with slag-pit provisions. This interpretation is indicated by especially the presence of large quantities of droplet slags at the Kalenga sites (see also Schmidt and Childs 1985: 56), lack of overall large number of flow slags as well as the absence of tuyère mould slags. Droplet slags were not discovered from the Ntuha site, possibly due to deposition and burial of the remains (see Background Chapter), but I have benefited from the microscopic data in terms of: (1) the absence of (clear) magnetite skins in the smelting slags from the two areas, and (2) the presence of large crystals in the slags indicative of a slow cooling process (see Figure 10.7). Finding (early) iron furnaces with slag-pit provisions in southern Tanzania is interesting, because slag-pit provisions have been associated with the (early or *Urewe*) iron smelting furnaces elsewhere in eastern Africa (see Schmidt and Avery 1983; Schmidt and Childs 1985; Schmidt 1988; Craddock *et al*. 2007; Iles and Martinón-Torres 2009). Although most of the (early) iron smelting furnaces elsewhere in eastern Africa were made of clay bricks (see Schmidt and Avery 1983; Schmidt

1988, 1997a, 2006), the Uhehe furnaces were made of clay rolls (see Lyaya 2012) and are very comparable to the *Urewe* furnaces from Buhaya, Rwanda and Burundi (see Schmidt 1997a; Craddock *et al*. 2007: 4; see also Humphris 2010).

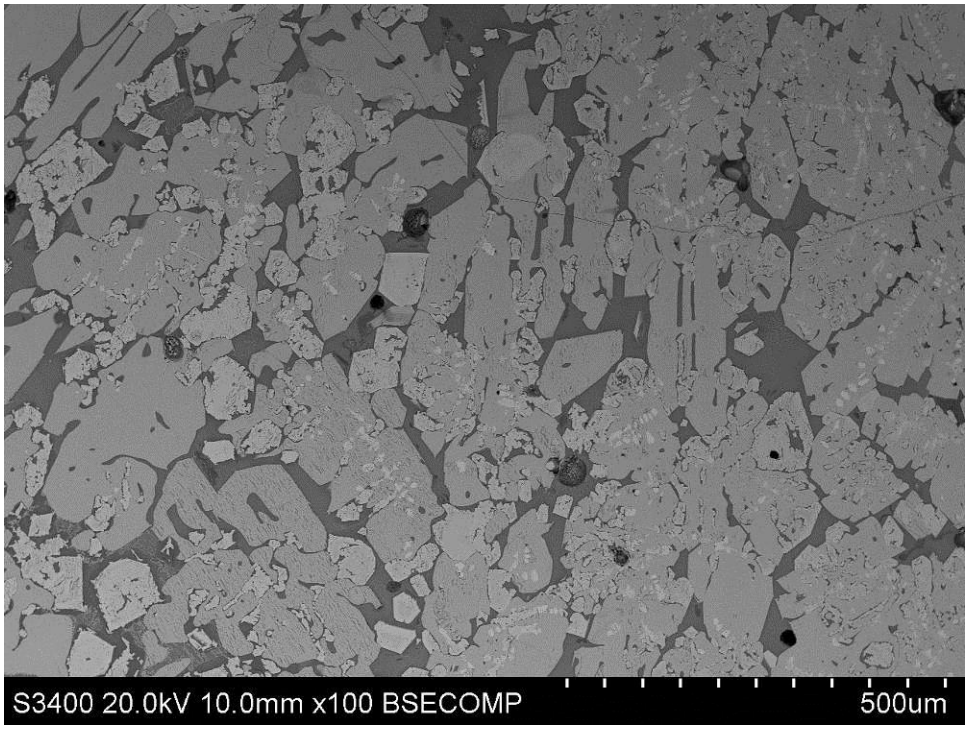

Figure 10.7: Microstructures of slowly cooled smelting slags from Ntuha in Lituhi. Note blocky crystals of fayalite (grey), magnetite (white grey), wüstite (white), glass (dark grey), and porosity (black)

10.6 Reduction Efficiency of Iron and Steel Production

The absence of (primary) free iron oxides in metallurgical slags is conventionally associated with efficient reduction of iron and steel, and vice versa (e.g. Morton and Wingrove 1969, 1972; Tylecote *et al*. 1971). Here the possible factors associated with the reduction efficiencies of the iron and steel production processes are discussed, in order to find out whether there were improvements in the reduction efficiencies of the processes over time and space. To start with, the *malungu* and *vintengwe* iron and steel production were both efficient processes respectively, because the smelting slags from

the former had only some sporadic wüstite and those from the latter had virtually no wüstite (see Chapters 5 & 6, on wüstite crystals). Chemically, the Ufipa smelting and refining slags, with FeO concentration of 42 and 51 wt% on average, are far more efficient than the smelting slags from central Kenya (see Iles and Martinón-Torres 2009) and southern Uganda (Humphris *et al*. 2009), with FeO concentration of *circa* 58 and 59 wt% respectively. For malungu and *vintengwe* processes, the possible use of high fuel: ore ratio, probably well above 1:1 as indicated by relatively the fuel ash oxides, more likely contributed to this end (e.g. Killick 1991; Childs 1996). In addition, the height of the *malungu* furnaces provided fairly long (*circa* 3 m) reduction zones for the ore to be reduced in the furnace stacks before slagging commenced (e.g. Childs 1996: 313; Killick 2004a: 108). The use of Mn-rich ore in iron smelting in Unyiha was beneficial as well, because 1 mol of each MnO and FeO combined with silica to form slags rich in knebelite crystals, instead of 2 mol of FeO were combined with silica to form fayalite-rich slags (see also Iles and Martinón-Torres 2009: 2323; Charlton *et al* 2010: 365; Iles 2011: 332-333). For the *vintengwe* processes: (1) it was perhaps less complicated to (just) complete the reduction of the wüstite alone left over by the *malungu* processes, and (2) it is also possible that the refiners controlled effective and standardised bellowing rates to produce such lean slags (see also Schmidt and Avery 1978; Gordon and Killick 1993).

The early iron production at Ntuha site in Lituhi was relatively inefficient, but the later steel production at Kigonsera was relatively efficient. The slags from the former had (primary) wüstite and those from the latter had no wüstite (see Chapter 7, on wüstite crystals). Chemically, the Ntuha smelting slags with FeO concentration of 66 wt% are comparable to the smelting slags of the Njanja in central Zimbabwe, with FeO concentration of *circa* 67 wt% (see Chirikure 2006). On the other hand, the Kigonsera

smelting slags with FeO concentration of 43 wt% on average are probably better than the smelting slags from Nyanga in eastern Zimbabwe with FeO concentration of *circa* 54 wt% (see Chirikure and Rehren 2004). The poorer efficiency of iron production at the Ntuha site was possibly due to the use of a very rich (magnetite) ore (see Kapinga 1990) that required that some of the iron oxides be sacrificed to form running slag (Morton and Wingrove 1972: 480) in case no fluxes were added into the charge (for addition of flux practices elsewhere, see Morton and Wingrove 1972: 478; Whiteman and Okafor 2003: 72; Chirikure 2006: 149; Craddock *et al*. 2007: 10). In addition, relatively poor efficiency may have been related to low fuel to ore ratio, perhaps, below 1:1, perhaps in order to save fuel. The combination of a low fuel to ore ratio and the proposed use of one tuyère per port, it can be argued, produced lower temperatures than the required CO/CO_2 to reduce most of the iron in the ore or slag (see also Morton and Wingrove 1969: 1557). With repeated experience, the later steel producers in the region possibly rectified the technical problems of their predecessors by (1) increasing the fuel to ore ratio, say above 1:1, (2) increasing the number of tuyères per port, from 1 to 4 tuyères per port (see Kapinga 1990; for the use of multiple tuyères elsewhere, see Chirikure 2006: 149; Humphris *et al*. 2009: 368; Rehren *et al*. 2007: 214), and (3) by the use of forced draft furnaces as opposed to the early natural draft ones. The combination of these factors perhaps provided the optimal smelting conditions for efficient reduction as well as production of steel (see also Tylecote *et al*. 1971; Chirikure 2006).

Early and later iron production processes in Kalenga were relatively less efficient, because the slags showed up primary wüstite (see Chapter 8, on wüstite crystals). Chemically, the smelting slags from Kalenga with FeO concentration of 62 wt% are better than the Ntuha slags, and by extension, they are also better than the smelting slags

from southern Africa with FeO concentration of *circa* 76 wt% (see Miller and Killick 2004: 36). One reason for the relative inefficiency of the Kalenga processes was possibly the use of a low fuel to ore ratio (see Rehren *et al*. 2007). In addition to a low fuel to ore ratio, the use of clay rolls to build the smelting furnaces in this area (see Chapter 8 and relevant appendices) supposedly had potential technical flaws. The use of clay rolls could have affected optimum temperature control in the furnaces, because expansion and contraction due to heating and cooling is likely to loosen the space between the clay rolls that in turn allow cool air to be drawn into the furnace as well as gas to escape from the furnace, albeit at low levels (see Tylecote *et al*. 1971: 351). In order to test this hypothesis, I will need in the near future to examine slags from similar furnace designs located in Usambara mountains in northern Tanzania (see Kiriama 1987; Schmidt 1988).

Lastly, iron production in Njombe was efficient, because the smelting slags had less (secondary) wüstite (see Chapter 9, on wüstite crystals). In terms of comparison, the smelting slags from Njombe, with FeO concentration of 59 wt% on average, are as good as the smelting slags of the Baganda in southern Uganda (see Humphris *et al*. 2009) and the Yoruba in western Nigeria (see Ige and Rehren 2003), both with FeO concentration of *circa* 59 wt%. To achieve this end, the Bena iron smelters may have used high fuel to ore ratio, say about 1:1. The use of tuyères with large internal diameters in combination with standardised bellowing rates possibly produced optimal CO/CO_2 ratio for the production of virtually lean slags (see also Schmidt and Avery 1978; Klapwijk 1986a). In addition, the use of Ti-rich iron ores indicated by the presence of ulvite spinels in the slags (see Chapter 9, on ulvite crystals) more likely contributed to the production of good slags rich in ulvite spinels instead of fayalite. We know that only 1 atom of iron of the (ilmenite) ore would be wasted in the slags in form of the ulvite crystals, instead of

2 atoms of iron wasted in the slags due to the formation of fayalite crystals (see Ige and Rehren 2003: 20). In sum, there are other *silent* factors including labour, time factor, social-cultural context, and skills and experience of the smelters and refiners that largely contributed to the production of such different slags in the southern highlands of Tanzania. Although these factors may not be directly signalled in the archaeological record, which does not mean that they were not part of the technology of iron and steel production. They were important and require more research attention if we want to fully grasp the knowledge of metal production.

10.7 Nature of the Smelting and Refining Final Products

Here I discuss the nature of the final products of the smelting and refining processes, and in addition I examine whether the final products of the processes were accidentally or intentionally produced. For the sake of clarity, I discuss the processes that generally produced (soft) iron on one hand, and those which produced high carbon steel on the other. The former include iron smelting in Lituhi (see Ntuha site), Kalenga, Sumbawanga, Mbozi, and Njombe, and the latter include (secondary) high carbon steel production in Sumbawanga and Mbozi, and (primary) high carbon steel production in Mbinga (see Chapters 5-9).

The production of (soft) 'bloomery' iron generally is indicated by (1) the presence of primary wüstite crystals in the slags (e.g. Tylecote *et al*. 1971; Bachmann 1982), and (2) the presence of irregular iron particles (micrograins) in the slags (see Tholander and Blomgren 1985; Tholander 1987, 1989). These two main features of less reducing furnaces describe well our smelting slags from Ntuha, Kalenga, Sumbawanga, Mbozi, and Njombe sites, although the slags from the first two areas had more wüstite than those from the last three areas with little wüstite (see Chapters 5-9). This means that while the smelters from the five areas all possibly produced soft iron, the yield of the

first two areas was lower than that from the last three areas (see Tylecote *et al*. 1971). These results more likely compare to the production of iron elsewhere in eastern Africa, for example; in Kenya (see Iles and Martinón-Torres 2009), Uganda (see Humphris *et al*. 2009), northwestern Tanzania (see Childs 1996), and northern Ufipa (see Mapunda 2010: 169-171). On the question of intentional versus accidental iron production, and based on systematic occurrences of wüstite and angular iron particles in the slags selected randomly, the evidence strongly suggests that iron smelters in the southern highlands of Tanzania intentionally wanted and systematically produced soft iron.

On the other hand, high carbon steel production in Sumbawanga, Mbozi, and Mbinga has been indicated by (1) the absence of wüstite crystals, and (2) the presence of regular iron droplets in the slags. In order to produce such good slags, the smelters and refiners controlled highly reducing conditions in the furnaces by the use of (1) high fuel to ore ratio, above 1:1 (e.g. Morton and Wingrove 1969, 1972; Tylecote *et al*. 1971), (2) standardised and optimal air supply rates (e.g. Schmidt and Avery 1978), and (3) optimal CO/CO_2 conditions in the furnaces (see Killick and Gordon 1989). Although iron droplets characterise blast furnace slags (e.g. Tholander and Blomgren 1985; Tholander 1987, 1989), the iron droplet chemical data (see Chapters 5-7 and relevant appendices) indicate that carbon concentration in them is heterogeneous, ranging from low to high carbon compositions. The variable carbon compositions of the iron droplets suggest that the final product, that formed when the droplets coalesced, was heterogeneous (solid) high carbon steel, with some sporadic pockets of cast iron (for similar results of production of high carbon steel with some cast iron pockets elsewhere, see David *et al*. 1989; Childs 1996; Schmidt 1997a). My solid high carbon steel production interpretation as opposed to liquid cast iron production is also strengthened by the high FeO concentration in the refining slags, of about 41 wt% in Mbozi and 52

wt% in Sumbawanga on average. Other factors kept constant, typical liquid cast iron *smelting* slags generally will have FeO concentration in the range of *circa* 5-13 wt% (see White 1980: 60-63; Crossley 1995: 410-1; Rehren and Ganzelewski 1995: 174). In addition, these refining slags are dominated by olivine minerals (see Chapters 5 & 6), but cast iron smelting slags are often glassy, with anorthite and pyroxene minerals (see White 1980: 61-62). The question whether or not the iron droplets represent the final (steel) product is a difficult one, but not impossible to address. Killick and Gordon (1989) have published two principal mechanisms of iron (and steel) production, namely, primary reduction of iron (and steel) directly from the ore, and the secondary reduction of the initially dissolved iron from the slag. If the Kigonsera smelting furnaces, for example, produced the direct high carbon steels through a so-called secondary iron reduction mechanism, where all of the iron oxide is initially dissolved in the slag from which it must then be recovered (van der Merwe and Avery 1982: 153; Killick and Gordon 1989: 123), then there is no doubt that the iron droplets were remnants of the drops which did not coalesce with the large lump of high carbon steel.

By extension, our results of high carbon steel production in the *vintengwe* furnaces, do not support Barndon's (2004: 89) suggestion of (soft) iron 'bloom' production in the *vintengwe* furnaces in Ufipa, but may rather support Wise's (1958: 110) interpretation that the *vintengwe* produced *ululu* (or *mlulu* in Swahili) [steel, own interpretation] and the *malungu* furnaces produced *untale* (or *mtale* in Swahili) [soft iron 'bloom', own interpretation]. The discovery of high carbon steel production in the (secondary) *vintengwe* furnaces also adds a new *secondary* pathway to steel production in Africa, because previously we had thought of *primary* pathways (for example, the Mbinga steel pathway) to steel production (see van der Merwe and Avery 1982, David *et al*. 1989; Childs 1996). Apart from that, our results on high carbon steel production bring into

question the association of the absence of wüstite in slags alone as a sole criterion for steel production (e.g. Ige and Rehren 2003: 20; Killick 2004a: 108), and suggests a need for a critical consideration of the presence of iron droplets as well. There is also almost no doubt that the high carbon steel production in Ufipa, Unyiha, and Umatengo was intentional, because all the refining and smelting slags selected at random systematically showed iron droplets, at a rate of about 4 to 15 per polished surface. It is noteworthy, however, that during the *open fire* smithing stage the high carbon steels were perhaps decarburised to low carbon steel tools (e.g. Mapunda 2010: 180).

10.8 Summary

I have discussed the research objectives of this thesis in relation to comparative macroscopic and microscopic data from the research area and published data from elsewhere especially in Africa. That is iron and steel producers in the region used highly refractory technical ceramics, both natural and forced draft furnaces were used, and ironworking in Ufipa and Unyiha was a three stage process. Liquid slag was either tapped, or drained to *special* pits outside the furnace, or drained down to the furnace slag-pit provisions. Most of the metal production processes in the region were efficient in terms of reduction, and the smelters aimed at the production of iron or steel. Based on this discussion, the following chapter presents conclusions of the project in relation to the main research question of this thesis.

11. Conclusion: Answering the Research Question

11.1 Preamble

In Chapter One, the research question of this thesis was presented: this work examines the relationship between macro- and microscopic variation of iron and steel production in the southern highlands of Tanzania. Here I reconsider this question in the light of the new findings (see Chapters 5-9) and the discussion of the research objectives (see previous chapter). As was predicted, the findings mostly point to a strong relationship between macro- and microscopic data variation. The relationship between the two sets of data include: the size of the smelting furnaces relating to the use of variable iron ores; the selection of clay for technical ceramics production in relation to refractory quality; the macro- and microscopic data for the presence of a three stage process of iron and steel production are shown to be related, and the size of the smelting furnaces relating to liquid slag handling methods. For the sake of clarity, each of these positions is discussed separately. The last two sections of this chapter provide recommendations and areas for future studies and a summary of the chapter.

11.2 Conclusions of the Thesis

First, there is a clear relationship between the macro-variation of the furnaces and the geochemistry of the slags, because the greatly variable smelting furnaces of the region possibly utilised iron ores with different geochemical signatures (see Table 11.1). This is a first dimension that clearly shows that the smelting furnaces of the region did not smelt iron ores with the same geochemistry. One possible explanation is that the

differences in the geochemistry of the smelted slags can in all probability be related to the geology and mineralogy of the region (see Pinna *et al*. 2004).

Table 11.1: Slag geochemistry of the iron and steel production furnaces in the southern highlands of Tanzania

Area (Ward)	Geo-chemistry	Source
Ufipa (Pito)	Al-rich	Lyaya *et al*. 2012; see also Wise 1958
Unyiha (Itaka)	Mn-rich	Chapter 6; *cf*. Brock and Brock 1965
Umatengo (Ntuha and Kigonsera)	Mn-rich and Si-rich	Chapter 7; *cf*. Kapinga 1990
Uhehe (Kalenga)	Zr-rich	Chapter 8
Ubena (Njombe)	Ti-rich	Chapter 9; *cf*. Sutton 1985

In addition to the geochemical signature differences of the slags, it is possible that the large furnaces of Ufipa and Unyiha utilised less FeO-rich (lateritic) ores (see also Brock and Brock 1965; Lyaya *et al*. 2012; elsewhere see Killick 1990; Pryce and Natapintu 2010), while the relatively small smelting furnaces of Umatengo, Uhehe, and Ubena may have utilised more FeO-rich iron ores (see also Sutton 1985; Kapinga 1990), but this needs ore sample analyses for further confirmation. By extension, this position is strengthened by the fact that the small *vintengwe* furnaces refined very rich iron (e.g. Barndon 2004; for similar findings elsewhere on the continent, see also Davison and Mosley 1988: 76; Whiteman and Okafor 2003: 72; Mapunda 2010: 99), although the *vintengwe* process meant to carburise iron to steel. I believe it is more likely that the use of particular iron ores by certain smelters depended on the geology and mineralogy of the areas they lived in. The Fipa and Nyiha largely live in the plains (see Willis 1966; Brock 1966), with flat marshes rich in (less FeO-rich) lateritic ores, noticeable especially during the rains by the (rusty and yellowish or orangish) colour of the water (*cf*. Greig 1937; Wise 1958). The Matengo and Bena live in the mountains, with perennial rivers full of especially Fe-rich black sands. It is no wonder that they smelted

such FeO-rich ores (*cf*. Sutton 1985; Kapinga 1990), because that is mostly available in these areas. Similarly, the smelting sites of the Hehe in Kalenga are located in the mountains, possibly closer to source of FeO-rich iron ores rich in zirconium as well. It is possible that the latter smelted FeO-rich ores, which required extra fluxes such as lime (see Chapter 8, on slag chemical data from Magubike 1) in order to reduce iron loss into the slag, although the addition of lime as flux seems to have been not efficient (see previous chapter, on technical efficiency). The size of the smelting furnaces may have depended on the internal and external demand of iron and steel. I strongly believe that smelting FeO-rich ores in big furnaces such as those of Ufipa would have created technical and practical difficulties for the production of iron. Whichever was the case, the association of furnace sizes and iron ores used was probably not so important to the smelters, because we do not know whether there were ore and furnace alternatives available for them to select (see Killick 2004b).

Second, there is a relationship between the selection of clay for the production of technical ceramics and the refractory quality of the clays. The iron and steel producers in Ufipa and Unyiha intentionally selected termite-mound clays for the production of the technical ceramics (furnaces and tuyères), because the clays were sufficiently refractory to withstand the temperatures conventionally required for the process of iron and steel production (*cf*. Childs 1996). These results do not lend support to the popular knowledge on the use of different clays for the production of furnaces and tuyères (see Freestone and Tite 1986). On the other hand, however, the iron and steel producers in Umatengo, Uhehe, and Ubena selected different clay sources for the production of ceramics for different technical purposes. In general terms, clays for the production of tuyères was more refractory (and in many cases more dimensionally stable) than those for the construction of the furnaces, pottery, and possible charging platforms (for the

case of Ntuha site). One possible explanation is that the tuyères were subjected to relatively higher temperatures inside the furnaces than the entire furnace walls, or pottery often buried at the base of the furnaces, or the possible charging platform which were clearly not subjected to the direct smelting fire inside the furnaces (see also Freestone and Tite 1986; Childs 1989a; Schmidt 1997a, 2006). The tuyères were critically important for the success of a smelt, because their collapse inside the furnaces would have halted or failed the smelting process. Therefore, and in order to reduce such risks of failing, they resorted to the use of better clays for the production of tuyères. To understand suitable clay qualities with certain precision, it could be argued that the smelters must have experimented with the clays technical qualities over a period of time. Whichever was the case, I can conclude with certainty that the smelters selected different clays with optimal refractory quality for the production of ceramics for different technical functions during the process of iron and steel production.

Third, the macroscopic evidence for the presence of a three stage process in Ufipa and Unyiha (*cf*. Mapunda 2010; Lyaya *et al*. 2012) is clearly related to the microscopic data in terms of the chemistry and mineralogy of the smelting and refining slags. Chemically, the findings (see Chapters 5 & 6) clearly point out that the *malungu* smelting process was less efficient than the *vintengwe* refining process. On the basis of the chemical data, it can be concluded that the two processes were technologically different (*cf*. Lyaya *et al*. 2012). Based on the mineralogical data in terms of the presence and absence of wüstite and iron droplet phases, the first smelting stage aimed at the production of impure soft iron, and the second refining stage aimed at the production of high carbon steel. Clearly this suggests the two stages were functionally different as well (*cf*. Lyaya *et al*. 2012), even if they are related stages in a production circle (*cf*. Killick 1990). The relationship of macro- and microscopic data on smelting

and refining in Ufipa and Unyiha can be used to confirm what Wembah-Rashid wrote in the 1960s about three stages of iron production (smelting, refining, and smithing) in Ufipa (1969: 66), or in those words written by Brock and Brock (1965: 98), that iron refining in Unyiha was conducted specifically for desired high quality 'iron' [steel, own interpretation].

Fourth and last, the size of the *smelting* furnaces especially in terms of the diameters is mostly related to the liquid slag handling techniques. The large smelting furnaces of Ufipa, Unyiha, Kigonsera, and Ubena, with external diameters *circa* 80 cm and above, employed the slag tapping techniques. Those small smelting furnaces of Ntuha and Kalenga, with relatively small external diameters *circa* 45 cm (see Chapter 8), employed the non-slag tapping techniques (see Chapters 8 & 9). Interestingly, the former group were recent metal producers, and the latter were relatively ancient metal producers; this might suggest that with time metal producers changed the techniques of handling the liquid slag (for similar results elsewhere in Ufipa, *cf.* Mapunda 2003b, 2010). The change in the technology was probably due to the need to increase the iron or steel yield in terms of the improved reduction efficiency (for details of the improved efficiency, see Chapters 5-9, or Mapunda 2010). It may have been due to possible increase in demand of the iron tools for agriculture, fishing, and hunting activities, assuming that the population had increased, but this is just one of several possible explanations.

As well as the relationship of the macro- and microscopic data presented above, I want to mention that the examination of the air supply mechanisms into the smelting and refining furnaces has concentrated on macroscopic data alone, because I have not developed ways of testing such mechanisms in scientific labs. The findings clearly show that the study of air supply should critically involve multifactors including: shape of the

proximal tuyère ends; the nature of the process; smelting versus refining; the size of the furnace and the number of tuyère ports per furnaces (for details, see Chapters 5-9).

11.3 Recommendations

There are three recommendations that have emerged in relation to this work.

First, because there is a close relationship between macro- and microscopic data, I recommend that students of African (iron) metallurgy should give equal priority to both field and laboratory approaches in order to comprehend fully archaeometallurgical phenomena. For example, macroscopic examination of smelting and refining slags alone cannot resolve the question of whether or not liquid slag was tapped, and it is also difficult to understand the presence of the refining slags (*not* the conventional primary smithing slags) based on microscopic examination alone, because they look *very* similar to the smelting slags. For the sake of clarity of the African slag classification, I would argue, it is necessary to start *always* with fieldwork, or rather examining the context of the archaeometallurgical remains, well before embarking on the technical studies that are equally important to improve our understanding of the archaeological phenomena (see Childs 1996; Holl 2009).

Second, the demonstration of a three stage iron and steel production tradition in Tanzania should awaken African archaeologists to the fact that they should *not* continue overlooking the possibilities of a refining stage that was geared to produce high carbon steel using the *vintengwe* furnaces, as opposed to the well known 'crucible steel'. The intentional production of the '*vintengwe* steel' supports the need to continue challenging the use of the (obsolete) phrase 'bloomery iron' in the context of African iron metallurgy. The phrase 'bloomery iron' has one inherent problem: it emphasises the production of *soft* iron alone, with less or no carbon. Its use in African contexts is extremely unhelpful, because it ignores the significant achievements of production of

direct primary carbon-rich steel (see van der Merwe and Avery 1982; David *et al*. 1989; Childs 1996) and secondary (high carbon) '*vintengwe* steel' (see Lyaya *et al*. 2012) in Africa. This work recommends that in order to avoid confusion on the classification of the three stage process, the role of matrix and provenance should be given due weight as laboratory analyses.

Third and last, examining the nature of the final products for the smelting and refining processes on the basis of carbon in the finished products (e.g. knives, hoes, axes) (e.g. van der Merwe and Avery 1982; Mapunda 2010) is problematic and incomprehensive. The carbon in the forged tool is far from a true representation of carbon in the smelting or refining process that produced it, because carbon in the smelted or refined material more likely will be decarburised during the *open fire* smithing process. Therefore, and in order to understand the more likely nature of the final products of the smelting and refining processes, I recommend that archaeometallurgists should study the respective slags. Equally important, I should note that low or medium carbon in the forged tool is what the smelters and refiners wanted, but they had to produce high carbon steels in the first or second stage.

11.4 Areas for Future Research

There are six avenues for future research in relation to this work.

First, although this work has demonstrated the presence of a three stage process in southern Tanzania, there is a clear need to conduct other research to look for this 'overlooked' African iron and steel production tradition elsewhere on the continent. It seems to have been followed in areas including Kenya (e.g. Kusimba 1996: 400), Malawi (e.g. van der Merwe and Avery 1982; Davison and Mosley 1988; Killick 1990), Zambia (e.g. Chaplin 1961), DRC (e.g. Mapunda 2010), Zimbabwe (e.g. Mapunda 2010), South Africa (e.g. Stayt 1931: 59-60, 1968: 60), and Burkina Faso (e.g. Timpoko

2003; Kiethéga 2009; Vincent Serneels, pers. comm. 2012). To this end and as recommended above, such work will need to use both field and laboratory approaches. In addition and for the case of Ufipa and Unyiha, the search for this 'forgotten' iron and steel tradition will need to be accompanied by the analysis of experimental smelting, refining, and smithing material, in order to compare with the archaeological data. In this way, I will establish a proper method for the search of the tradition elsewhere.

Second, since this work has discovered the production of carbon-rich steel in Ufipa, Unyiha, and Umatengo (in Kigonsera), there is a need to conduct ethnographic surveys in these societies with a view to collecting archaeometallurgical iron or steel tools for metallography. Metallographic study of the tools will aim at investigating the nature of the forged iron or steel tools in terms of their carbon content.

Third, this work in Ubena and Unyiha concentrated on later iron production, but in the near future it will be necessary to look at the material from the early iron production in the areas. Among other things, this will help to find out whether or not the smelting technology in terms of the liquid slag handling techniques and the reduction efficiency was similar to the later or changed over time.

Fourth, most of the sites examined herein are yet to be properly dated. This will be important in order to examine fully the temporal distribution and variation of ironworking in the southern highlands of Tanzania.

Fifth, although this work has discovered numerous archaeological sites in the sampled five districts of the region, it is imperative that research be conducted in the other districts as well, in order to compare and examine further the variation of iron and steel production in the region.

Sixth and last, this work has concentrated on the inorganic material of the production of iron and steel in the region. However, there is a need to study equally the (ethnographic)

plant and animal species that were part of the metal production process (see Mapunda 2003a; Lyaya 2008a, 2011), in order to establish whether or not the metal producers were species-selective (e.g. Mapunda 2003a; Lyaya 2011) or omnivorous consumers (e.g. Schmidt 1997b; Stromquist *et al*. 1999). It will also be essential to understand the reasons for the selection of some animal and plant species for the process of iron production (*cf*. Plug and Pistorius 1999).

11.5 Summary

Based on the findings, this chapter has shown that (African) iron and steel production is both macroscopically and microscopically greatly variable. It also demonstrated that macro- and microscopic data are by and large related, especially in terms of (1) the size of the smelting furnaces and respective iron ores, (2) the technical ceramics and the refractory quality, (3) the presence of a three stage process of iron and steel production, and (4) the size (or diameter) of the smelting furnaces and liquid slag handling methods. It further showed that later iron and steel production was generally more efficient than the early iron production in the southern highlands of Tanzania.

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Appendix 1: Chapter 1 Appendices

Appendix 1.1: Extra Key Term Definitions

Amalombwe are renowned (traditional) midwives in Ufipa

Bio-archaeometallurgy refers to the study of plant and animal species that were part of the metal production process (see Mapunda 2003a; Lyaya 2011).

Indipa and ***Imbaba*** refer to two ritualistic pottery that were buried under the furnace base in Umatengo (see Kapinga 1990).

Intangala is a special bag that kept the smelting (refining) medicines in Ufipa

Ipembo or ***impembo*** refers to the smithing hearth or smithing site in Ufipa

Katukutu is a short (*circa* 1 m) globular smelting furnace pre-dating the malungu in Ufipa (Mapunda 1995b) and Unyiha (Ngonadi 2010).

Kikolombi refers to a special tuyère that was used for peeping progress in the smelting furnace located at the bottom of the smelting furnaces (see Kapinga 1990).

Kuseya refers to the process of beneficiation of the mdapu

Matendi or ***matende*** (***litende*** sing.) refer to the smelting furnaces in Umatengo and Ubena

Mdapu refers to the (black sand) iron ores in Njombe

Mlepulo refers to the slag tapping hole or drainage in Ubena

Palinyina refers to the 'rake hole' of the malungu furnaces in Ufipa (see Mapunda 2010).

Ubena refers to the land (or area) inhabited by the Bena Bantu-speaking people in the Njombe district. Note that there are other minority tribes in Ubena, including the Kinga and Hehe (LOT 2009: 20). It is assumed that (later) iron technology in Ubena (or

Njombe) was associated with the Bena, but this has been unfortunately difficult to ascertain.

Ufipa refers to the land (or area) inhabited by the Fipa Bantu-speaking people of the Rukwa region. Note that there are other minority tribes in Ufipa, including the Swahili (LOT 2009: 94). It is assumed that (later or malungu) iron technology in Ufipa was associated with the Fipa, but this has been unfortunately difficult to ascertain.

Uhehe refers to the land (or area) inhabited by the Hehe Bantu-speaking people of the Iringa region. Note that there are other minority tribes in Uhehe, such as the Bena, Kinga, Pangwa (LOT 2009: 22). It is assumed that iron technology in Uhehe (or Rural Iringa) was associated with the Hehe, but this has been unfortunately difficult to ascertain.

Ululu refers to the product of the refining process as opposed to *untale* below.

Umatengo refers to the land (or area) inhabited by the majority Matengo Bantu-speaking people in Mbinga. Note that there are other minority tribes in Umatengo, such as the Ngoni, Nyasa, Mpoto, and Manda (LOT 2009: 98). It is assumed that (later) iron technology in Umatengo (or Mbinga) was associated with the Matengo, but this has been unfortunately difficult to ascertain.

Untale refers to the product of malungu (smelting) process as opposed to *ululu* above.

Untalembe is a special stick on which termite mound (wet) clay was wrapped on in order to produce tuyères for the malungu and vintengwe furnaces.

Unyiha refers to the land (or area) inhabited by the majority Nyiha Bantu-speaking people in Mbozi district. Note that there are other minority tribes in Unyiha (or Mbozi), such as the Nyamwanga, Ndali, Nyakyusa, and Kinga (LOT 2009: 64). It is assumed that (later or malungu) iron technology in Unyiha was associated with the Nyiha, but this has been unfortunately difficult to ascertain.

Appendix 2: Chapter 2 Appendices

Appendix 2.1: Keay (1959) classification scheme of the vegetation life forms of Tanzania

The vegetation life forms included (1) montane evergreen forest, (2) montane communities with afro-alpine communities, (3) forest savanna mosaic, (4) coastal forest-savanna mosaic, (5) montane communities-undifferentiated, (6) moist forest at low and medium altitudes, (7) undifferentiated-relatively dry types, (8) south-eastern areas-with abundant Brachystegia and Jurbernardia, (9) wooded steppe with abundant Acacia and Commiphora, (10) undifferentiated-relatively moist types, (11) Itigi type, and (12) tropical types-sub desert steppe and Luanda type life forms.

Appendix 2.2: Lind and Morrison (1974) classification scheme of the vegetation life forms of Tanzania

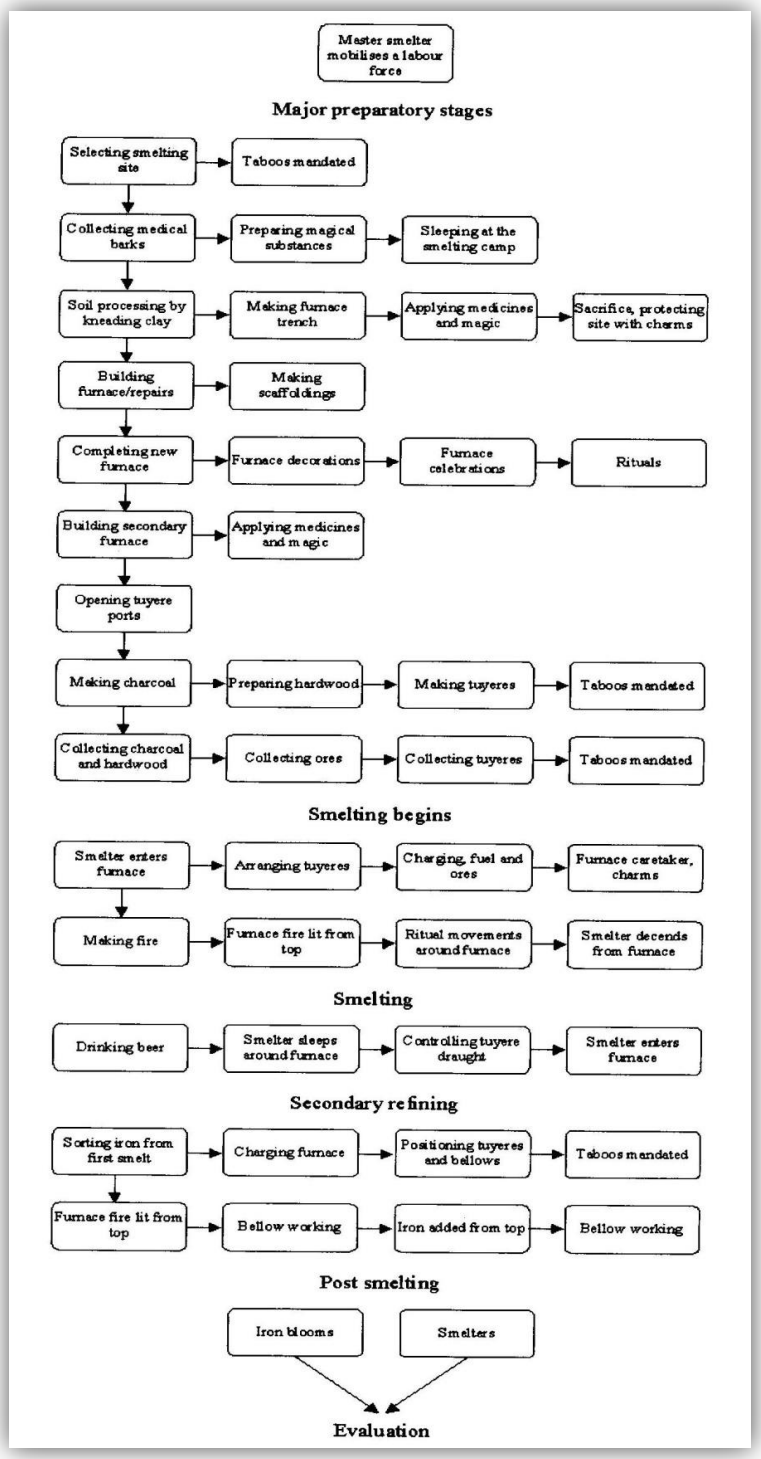
The vegetation life forms included (1) forest, (2) woodlands, (3) bushlands, (4) grassland, (5) bushed grasslands, (6) wooded grasslands, (7) dwarf shrub grasslands, (8) barren land, and (9) permanent swamp life forms.

Appendix 2.3: Bio-archaeometallurgical (plant) species of iron production process of the Hehe in Kalenga

No.	Local name (in Hehe)	Botanical name (Genus and species)	Botanical Family
1	Mgunga	*Acacia robusta* Burch.	Mimosaceae
2	Myombo	*Brachystegia boehmii* Taub.	Caesalpiniaceae
3	Mtamba	*Ficus cycomorus* L.	Moraceae
4	Mpinati	*Julbernardia globiflora* (Benth.) Troupin	Caesalpiniaceae
5	Mtaponzi	*Ozonoa infignis* Delile	Anacardiaceae
6	Mvanga	*Pericopsis angolensis* (Baker) Meeuwen	Papilionaceae
7	Msangara	*Pterocarpus tinctorius* Welw.	Papilionaceae
8	Mtunumbi	*Rhus natalensis* Krauss	Anacardiaceae

Appendix 3: Chapter 3 Appendices

Appendix 3.1: Chaîne opératoire for a three stage process in Ufipa (from Barndon 2004: 92)



Appendix 4: Chapter 4 Appendices

Appendix 4.1: Guiding Questionnaire

Macroscopic and Microscopic Variation of Iron and Steel Production in the Southern Highlands of Tanzania

Edwinus Chrisantus LYAYA
UCL Institute of Archaeology

Date: _____

Dear respondent,

This is a doctoral field research project on iron and steel production in the southern highlands of Tanzania including Iringa, Mbeya, Ruvuma, and Rukwa regions. This questionnaire aims at gathering ethnographic information from (recent) iron smelters with relevant information on the subject.

This research is significant, because it will help us to understand the technology of iron and steel production. It is imperative to do this, because such information is disappearing quickly and almost all actual smelters are gone. We can assure you that all the information you provide to me will be kept confidential and anonymous; so feel free to provide the information you have on the furnaces, tuyères, bellows, medicines, rituals and symbolism of iron and steel production

A: Identity

1. Name:----------(optional)
2. Occupation:----------
3. Age:----------
4. Gender:----------
5. Clan:----------
6. Tribe:----------

B: Ironworking Knowledge Acquisition

1. How did you learn about ironworking? (Circle as appropriate)
   (a) Learnt it through my father
   (b) Learnt it through my grandfather
   (c) Learnt it from other ironworkers
2. If you acquired this technology from your father or grandfather, do you remember how old you were?

   ----
3. How often did you observe or participate in the smelting activity?

---

4. Can you tell what was your specialization in relation to this technology?(Circle as appropriate)
   (a) Smelter
   (b) Refiner
   (c) Smith
   (d) Fuel or wood collection
   (e) Charcoal preparation
   (f) Mining or ore preparation
5. If you were requested to **re-smelt**, **re-refine**, or **re-forge** today, do you think you can voluntarily do it correctly?(Delete the bolded options as appropriate)

C: Iron Smelting Knowledge

1. Do you remember where exactly smelting activities took place? (Circle as appropriate)
   (a) Secluded from settlements in the bushes
   Can you provide the reasons for this seclusion?

   (b) Smelting activities took place in settlements and were not secluded
   Can you tell the reasons for this preference?

---

2. Do you remember what things or steps were needed before the actual smelting activities began? (Mention in a correct series if possible)
   (a) ---
   (b) ---
   (c) ---
   (d) ---
   (e) ---

(f) ----------

(g) ----------

(h) ----------

3. What do you remember about the type of furnace design that you went for iron smelting?

(a) Height of the furnace

(b) Shape of the shaft inside or outside

(c) Decorated or not decorated furnace

(d) Symbolized furnace e.g. with breasts

(e) Furnace construction materials (circle as appropriate)

(I) Furnace made up from prepared bricks

(II) Furnace made up of prepared clay slabs

(III) Furnace made up of wet clay

(IV) Other materials (mention):

(f) Number of tuyère-ports per furnace

(g) Number of tuyères per port

(h) Number of peep hole per furnace

(i) Mode of operation (circle as appropriate)

(I) Natural-draft operation

(II) Forced-draft operation

(III) Both natural and forced-draft operations

(j) Did you had other choices of furnace designs, but you did not want them (Explain and give reasons)

---

4. Can you remember about the type of clays used to construct smelting furnaces? (Explain)

(a) Source

(b) Transportation to the site (who were specifically involved?)

(c) Tempered or not?(If tempered give the reason for this)

(d) Preparation of the clays (who were specifically involved?)

---

5. Can you remember about the types of tuyères you made for the smelting furnace?

(a) Length of the tuyères

(b) Can you approximate the diameter or width of these tuyères

---

(c) Types of clays to make them (circle as appropriate)

(I) The same as furnace clays

(II) Different clays from furnace clays

(III) Both types above were used

(d) If different types of clays were used, please answer the following:

(I) Source

(II) Transportation (who were specifically involved?)

(III) Preparations (who were specifically involved?)

(IV) Tempered or not? (If tempered give reasons)

(e) Which design were the tuyères? (Circle as appropriate)

(I) Flared proximal end

(II) Flared distal end

(III) Non-flared tuyères (same diameter through the body to both ends)

(IV) Mixture of both types

6. Do you remember on the following in relation to the types of iron ores that you smelted?

(a) Type of iron ore (name them, and give reasons for their use)

Mention: ---

Reasons: ---

(b) Describe their appearance and colour

Appearance

Colour

(c) How did you source or prospect them?

(d) What other types of iron ores those were available, but you did not use them? (mention and give reasons)

Mention: ----------

Reasons: ----------

(e) How did you collect or gather them? (Explain)

(f) Were the iron ores beneficiated before roasting or smelting whichever was done after beneficiation?

------Reasons: ----------

(g) Describe the size of the ore that were charged into the furnace

---

(h) How were the ores transported to the smelting site?

(i) In any case, were women involved in either ore collection or transportation?

---

7. Do you remember the types of trees that were used to produce charcoal for smelting

   (a) Name the trees

   (b) Why were these tree species selected for charcoal making? (Give reasons with specific examples of trees e.g. species X because it gives enough sparks)

   (c) What could have or happened if these preferred species were depleted by use or abuse?

   (d) Do you remember if these trees were very special in the ironworking society? (Explain with examples if possible)

---

8. Can you remember how much ore was charged into the smelting furnace in relation to charcoal? (Please explain and give ore to charcoal ratio estimates if possible in terms of buckets or baskets used)

---

9. Can you remember when smelting had begun, what other materials were also charged into the smelting furnace other than ore and charcoal? (Mention and give reasons if possible)

   Mention:

   Reasons:

   ---

10. Do you remember how flowing slag in the smelting furnace was collected? (Explain whether it cooled at the bottom of the furnace, or it was tapped outside the smelting furnace)

---

11. How many times did the initial smelting furnace serve for? (Explain and give reasons)

---

12. Do you remember where was the smelted bloom taken to after smelting? (Circle as appropriate)
    (a) Traditionally the smelted bloom was taken to a small refining furnace for purification as it contained lots of impurities, so it had to be refined before the actual smithing process
    (b) Traditionally this bloom was ready to be forged into artefacts, so it was taken directly to a smithing hearth
    (c) Traditionally it depended on what came out, if it was almost pure it was ready for forging implements, and if it was relatively impure it had to be refined in the small furnace

    If your answer to question 12 was (a) or (b), continue with section D question 1, but it you answered (b) please go to section E question 1.

D: Bloom Refining Knowledge

1. Do you remember where was the refining process situated?
    (a) Distance in relation to smelting furnace (estimate distance in metres, and reasons for this)

    Distance: ----------

    -----Reasons: ----------

    (b) Describe the shape of the shaft inside or inside

    (c) Direction in relation to smelting furnace

    Direction: ----------

    ------Reasons: ----------

(d) Did it transpire that sometimes refining activities took place in or near settlements? (Explain and provide the reasons for this)

Answer: ---

Reasons: ---

(e) Was there certain circumstances where refining activities neither were conducted contiguous to smelting site(s) nor in or near settlements, but took place somewhere in the bushes or away from settlements if you prefer? (Explain and give reasons)

Explanation: ---

Reasons: ---

---

2. Can you recall clearly on whether the refiners were actually the same smelters or not? (Circle as appropriate)
   (a) Refiners were exactly the same smelters, they did smelting and then went on with refining the smelted bloom
   (b) Refiners were actually different craftsmen from smelters, and in fact this technology was their own specialization
3. What do you remember about the following in relation to refining furnaces?
   (a) Height of the furnace

   (b) Describe the shape of the shaft inside and outside

(c) The diameter at the base and the top

(d) Decorated or not decorated furnace

(e) Symbolized furnace e.g. with breasts

(f) Furnace construction materials (circle as appropriate)

(V) Furnace made up from prepared bricks

(VI) Furnace made up of prepared clay slabs

(VII) Furnace made up of wet clay

(VIII) Other materials (mention):

(g) Number of tuyère -ports per furnace

(h) Number of tuyères per port

(i) Was there any slag-hole?

(j) Mode of operation (circle as appropriate)

(IV) Natural-draft operation

(V) Forced-draft operation

(VI) Both natural and forced-draft operations

(k) Did you had other choices of furnace designs, but you did not want them (explain and give reasons)

---

4. What do you remember about types of clays used to construct refining furnaces?
   (a) Where did you get the clays for refining furnace construction? (Provide the source and explain if this was the same source for smelting furnace clays)

   Source:----------

   ----------The same as smelting furnace clays? ----------

   (b) If the source was relatively far from refining site, explain how you transported these to the site? (who were involved)

   (c) Do you remember if you added temper into it during preparation of the clays?

   Answer: ----------

   Reasons: ----------

   ---

5. Do you remember whether refining process employed new tuyères or they used similar smelting tuyères?

(a) Explain whether new or old smelting tuyères were used

(b) If refiners used new tuyères, what could have been the difference between the two types?

(c) Do you remember if women were involved in clay preparation or construction of tuyères? (Explain and give reasons)

Explanation: ---

Reasons: ---

---

6. Do you remember the types of trees that were used to produce charcoal for smelting

(a) Name the trees

(b) Why were these tree species selected for charcoal making? (Give reasons with specific examples of trees e.g. species X because it gives enough sparks)

(c) What could have or happened if these preferred species were depleted by use or abuse?

(d) Do you remember if these trees were very special in the ironworking society? (Explain with examples if possible)

---

7. How did you charge the refining furnace?

(a) Do you remember how many baskets or buckets [or any other unit of measurement] of charcoal did you charge into the refining furnace?

(b) Do you also remember how many buckets (or kilograms) of the bloom was charged into the furnace?

---

8. Did you charge other materials into the refining furnace other than bloom and charcoal? (Mention them and give reasons and quantity)
   (a) Mention:

   (b) Reasons:

   (c) How much of each of these were actually put into the refining furnace?

   ---

9. Do you remember how slag in the refining furnace was collected? (Explain whether it cooled at the bottom of the furnace, or it was tapped outside the smelting furnace)

   ---

10. How many times did the initial refining furnace serve for? (Explain and give reasons)

---

11. What kind of rituals was performed in this second stage of ironworking?

---

12. Where was the refined bloom or almost pure iron metal taken to? (Explain if it was taken to local smiths, foreign smiths, or traders, etc)

E: Iron Smithing Knowledge

1. Do you remember where smithing activities took place? (Explain and provide reasons)

   Explanation:---

   Reasons:---

   ---

2. What was the iron smithing structure, furnace or hearth? (Explain)

---

3. What do you remember about smithing tuyères?
   (a) Did you make new or you used similar tuyères from either smelting or refining processes?

   Reasons: ---

   (b) If you made new clay-tuyères, what type of clays did you use?

   (c) Did you temper your clays? (Mention materials and reasons)

   Materials: ---

   Reasons: ---

   (d) If they were non-clay tuyères, how did you make them?

   ---

4. What types of bellows did you use during iron smithing? (Explain)

---

5. Do you remember what other accessories were necessary for smithing process?

---

6. How were women involved in the smithing activities?

---

7. Do you remember the types of trees that were used to produce charcoal for smelting

   (a) Name the trees

   (b) Why were these tree species selected for charcoal making? (Give reasons with specific examples of trees e.g. species X because it gives enough sparks)

(c) What could have or happened if these preferred species were depleted by use or abuse?

(d) Do you remember if these trees were very special in the ironworking society? (Explain with examples if possible)

---

8. Were smiths the same as smelters or refiners? (Explain)

---

9. What kind of rituals was performed in this smithing stage of ironworking?

---

10. What types of utilitarian tools were forged? (Mention and give their functions)

---

11. Do you remember if there were non-utilitarian tools that were being manufactured?

---

12. What seasons were smithing activities taking place?

---

13. Can you remember how many times a smithing site could have been used?

F: Fall of Ironworking Knowledge

What factors led to the fall of ironworking in this part of the country?

END

Thank you so much for your co-operation, and as I said in the introduction all this information will be kept confidential and anonymous.

Appendix 4.2: List of the informants from the five research area districts
4.2a: Informants in Ufipa

No.	Name	Age	Gender	Tribe	Village	nterviewed
1	Alberto Nicolaus Malimbo	91	M	Fipa	Katumba-Azimio	26/08/2011
2	Damian Stephano Malimbo	77	M	Fipa	Katumba-Azimio	28/08/2011
3	Ernest Alberto Mwanisawa	62	M	Fipa	Katumba-Azimio	01/09/2011

4.2b: Informants in Unyiha

No.	Name	Age	Gender	Tribe	Village	Interviewed
1	Alihoka Mponda	66	M	Nyiha	Itaka	16/09/2011
2	Allan Mdolo	48	M	Nyiha	Itaka	14/09/2011
3	George Mwasenga	50	M	Nyiha	Itaka	14/09/2011
4	Gibson Mponzi Nkota	68	M	Nyiha	Malolo	18/09/2011
5	Gideon Nyerere	72	M	Nyiha	Itaka	11/09/2011
6	Jonas Elia Mwanakulya	77	M	Nyiha	Itaka	09/09/2011
7	Kunzitwe Mwashilingi	98	M	Nyiha	Itaka	13/08/2010
8	Pattison Helahela	71	M	Nyiha	Itaka	12/09/2011
9	Thomas Michael Munduwi	60	M	Nyiha	Itaka	14/09/2011
10	Thomas Mwampumba Nkota	84	M	Nyiha	Malolo	18/09/2011
11	Watison Mwashiwili	68	M	Nyiha	Itaka	17/09/2011
12	Zawadi Mpendakazi Mwasenga	71	M	Nyiha	Itaka	16/09/2011

4.2c: Informants in Umatengo

No.	Name	Age	Gender	Tribe	Village	Interviewed
1	Adam Alloys Komba	47	M	Matengo	Kigonsera	28/08/2010
2	Barnabas Kawonga	75	M	Matengo	Minazi	08/09/2010
3	Bertram Nkondola	75	M	Matengo	Minazi	09/08/2010
4	Costantine Oswald Millinga	89	M	Matengo	Mbinga	31/08/2010
5	Fr Vitus Kapinga	60	M	Matengo	Luanda	02/09/2010
6	Frank Jackson Sewando	40	M	Matengo	Mkulusi	08/09/2010
7	Philbert Maurus Kinunda	63	M	Matengo	Kigonsera	27/08/2010
8	Philoteus Komba Pesalela	57	M	Matengo	Mkulusi	07/09/2010

4.2d: Informants in Uhehe

No.	Name	Age	Gender	Tribe	Village	Interviewed
1	Zuberi Waitala	50	M	Hehe	Kalenga	20/08/2011

4.2e: Informants in Ubena

No.	Name	Age	Gender	Tribe	Village	Interviewed
1	Augostino Mtikwa	57	M	Bena	Mjimwema	10/07/2008
2	Elia Mng'ongo	70	M	Bena	Mjimwema	04/07/2008
3	John Akin Fute	53	M	Bena	Mjimwema	15/09/2011
4	Martina Sadala	64	F	Bena	Mjimwema	13/07/2008
5	Samwel Mtikwa	68	M	Bena	Mjimwema	06/07/2008
6	Tabita Mchungwa	75	F	Bena	Mjimwema	13/07/2008

Appendix 4.3: Certified and recommended values of the XRF reference materials for the technical ceramics
4.3a: NBS 679 Brick clay

4.3b: SARM 69 Ceramic-1

4.3c: SO-1 Reference soil

Appendix 4.4: Certified and recommended values of the XRF reference materials for the iron slags
4.4a: BCS 301 Lincolnshire iron ore

MAIN EDITION

British Chemical Standards

issued by

Bureau of Analysed Samples, Ltd.

Certificate of Analyses

B.C.S. No. 381 BASIC SLAG

The material for this standard was specially selected from slag produced at the British Steel Corporation, Corby Works. It was ground and graded to pass a 200 μm (80 mesh) sieve.

Prepared under rigorous laboratory conditions and, AFTER STANDARDIZATION BY ANALYSTS IN GREAT BRITAIN, issued by the Bureau of Analysed Samples, Ltd.

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ANALYSES

ALL RESULTS RELATE TO THE DRIED (105°C) SAMPLE

Analyst No.	Total P_2O_5 %	Cit-Sol P_2O_5 %	SiO_2 %	Total Fe %	FeO %	Al_2O_3 %	V_2O_5 %	TiO_2 %	Cr_2O_3 %	MnO %	CaO %	MgO %	S %
1	15·78	15·42	8·73	13·22	3·59	0·72	0·94	0·32	0·32	3·17	49·2	0·95	0·19
2	15·61	15·21	8·91	13·32	3·60	0·62	0·93	0·34	0·33	3·07	49·6	0·93	0·19
3	15·75	15·00	8·68	13·21	3·76	0·62	0·96	0·39	0·31	3·19	49·3	0·98	0·16
4	15·83	15·00	8·77	13·47	3·81	0·74	0·92	0·35	0·33	3·10	48·8	1·12	0·20
5	15·73	15·32	8·75	13·24	3·58	0·73	0·93	0·36	0·37	3·30	48·8	1·02	0·20
6	15·78	15·13	8·68	13·26	3·60	0·66	1·00	0·33	0·30	3·08	49·0	1·11	0·18
7	15·83	15·42	8·78	13·40	3·87	0·64	0·90	0·30	0·36	3·29	48·9	1·03	0·18
8	15·68	15·15	8·96	13·22	3·71	0·66	0·98	0·38	0·34	3·10	48·6	1·12	0·20
Average	**15·7–**	**15·2–**	**8·78**	**13·3–**	**3·69**	**0·67**	**0·94**	**0·35**	**0·33**	**3·16**	**49·0**	**1·03**	**0·19**

The above figures are those which each analyst has decided upon after careful verification

[P.T.O.

ECSC - CECA - EGKS

EUROPEAN COAL AND STEEL COMMUNITY
COMMUNAUTÉ EUROPÉENNE DU CHARBON ET DE L'ACIER
EUROPÄISCHE GEMEINSCHAFT FÜR KOHLE UND STAHL

EURO - STANDARD No. 681-1 IRON ORE

CERTIFICATE OF ANALYSES

Laboratory Means (4 values), all relate to the dried (105°) sample*

Line No.	%Fe	%Si	%Ca	%Mg	%Al	%Ti	%Mn	%P	%S	%Na	%K
1	—	—	2·595	0·8440	5·430	—	0·2108	—	0·0855	0·0598	—
2	33·00	8·111	2·610	0·8500	5·451	0·2580	0·2138	0·8481	0·0958	0·0598	0·4600
3	33·02	8·242	2·662	0·8500	5·512	0·2775	0·2148	0·8600	0·0968	0·0605	0·4675
4	33·05	8·250	2·718	0·8738	5·518	0·2826	0·2162	0·8600	0·0974	0·0610	0·4725
5	33·08	8·252	2·718	0·8742	5·525	0·2866	0·2168	0·8608	0·1004	0·0628	0·4735
6	33·09	8·258	2·754	0·8750	5·530	0·2869	0·2175	0·8673	0·1006	0·0637	0·4735
7	33·10	8·258	2·756	0·8750	5·532	0·2870	0·2178	0·8682	0·1009	0·0638	0·4763
8	33·11	8·292	2·776	0·8812	5·580	0·2875	0·2194	0·8685	0·1018	0·0652	0·4814
9	33·15	8·302	2·808	0·8825	5·599	0·2880	0·2200	0·8738	0·1030	0·0662	0·4850
10	33·18	8·312	2·815	0·8832	5·600	0·2888	0·2200	0·8748	0·1042	0·0665	0·4850
11	33·20	8·318	2·832	0·8865	5·608	0·2890	0·2216	0·8750	0·1045	0·0672	0·4850
12	33·24	8·328	2·835	0·8868	5·670	0·2895	0·2225	0·8755	0·1050	0·0690	0·4860
13	33·28	8·340	2·835	0·8900	5·682	0·2900	0·2238	0·8800	0·1066	0·0696	0·4875
14	33·29	8·348	2·850	0·8919	5·698	0·2948	0·2250	0·8830	0·1078	0·0700	0·4889
15	33·29	8·368	2·852	0·8950	5·705	0·2951	0·2275	0·8900	0·1080	0·0710	0·4925
16	33·30	8·378	2·852	0·9000	5·708	0·2955	0·2300	0·8900	0·1082	0·0740	0·4970
17	33·31	8·396	2·890	0·9062	5·717	0·2980	0·2300	0·8930	0·1085	0·0742	0·4995
18	33·32	8·402	2·894	0·9065	5·730	0·3015	0·2320	0·8940	0·1090	0·0750	0·5005
19	33·36	8·405	2·900	0·9100	5·758	0·3063	0·2325	0·8990	0·1090	0·0852	0·5025
20	33·38	8·430	2·955	0·9150	5·780	0·3100	0·2325	0·9010	—	0·0860	0·5060
21	33·45	—	2·988	0·9154			0·2350	0·9125		—	0·5069
M_M	33·21	8·315	2·804	0·8853	5·617	0·2903	0·2228	0·8787	0·1028	0·0685	0·4864
s_M	0·13	0·077	0·103	0·0204	0·105	0·0110	0·0071	0·0164	0·0060	0·0075	0·0132

Line No.	%F	%V	%Cr	%Ni	%C
1	0·1650	0·0718	0·0372	0·0140	—
2	0·1725	0·0725	0·0378	0·0148	1·752
3	0·1754	0·0730	0·0385	0·0148	1·760
4	0·1820	0·0734	0·0392	0·0148	1·762
5	0·1840	0·0737	0·0398	0·0149	1·780
6	0·1858	0·0742	0·0398	0·0149	1·783
7	0·1910	0·0746	0·0400	0·0150	1·784
8	0·1937	0·0750	0·0402	0·0150	1·789
9	0·1951	0·0780	0·0408	0·0151	1·794
10	0·1960	0·0790	0·0412	0·0155	1·796
11	0·1985	0·0803	0·0418	0·0158	1·800
12	0·1996	0·0813	0·0419	0·0164	1·828
13	0·2000	0·0815	0·0430	0·0165	1·838
14	0·2012	0·0822	0·0435	0·0170	1·841
15	0·2025	0·0825	0·0440	0·0170	1·845
16	0·2118	0·0830	0·0442	0·0175	1·848
17	0·2175	—	0·0449	0·0180	1·880
18	0·2200		0·0456	0·0190	
19			—	—	
20					
M_M	0·1940	0·0772	0·0413	0·0159	1·805
s_M	0·0148	0·0041	0·0025	0·0014	0·037

%Pb	%Co	%As	%Fe^{++}	%H_2O^+
0·0054	*0·0063*	*0·0090*	*6·587*	—
0·0055	*0·0063*	*0·0094*	*6·600*	*9·02*
0·0059	*0·0067*	*0·0095*	*6·606*	*9·55*
0·0060	*0·0070*	*0·0095*	*6·650*	*9·58*
0·0060	*0·0070*	*0·0098*	*6·675*	*9·69*
0·0062	*0·0072*	*0·0100*	*6·680*	*10·03*
0·0063	*0·0072*	*0·0102*	*6·700*	*10·10*
0·0063	*0·0075*	*0·0102*	*6·705*	*10·27*
0·0068	*0·0077*	*0·0103*	*6·725*	*10·40*
0·0070	*0·0078*	*0·0105*	*6·730*	*10·42*
0·0073	*0·0080*	*0·0108*	*6·800*	*10·46*
0·0075	*0·0088*	*0·0115*	*6·810*	*10·79*
0·0075	*0·0088*	*0·0122*	*6 825*	*10·84*
0·0079	*0·0089*	*0·0125*	*6·896*	*10·86*
0·0080	*0·0090*	*0·0135*	*6·907*	*11·32*
0·0087	*0·0090*	*0·0148*	*6·918*	
0·0088	*0·0092*	—	*6·920*	
0·0088	*0·0110*		*7·012*	
0·0089				
0·0090				
0·0072	*0·0080*	*0·0109*	*6·764*	*10·24*

M_M: Mean of the Intralaboratory means. s_M: Standard deviation of the Intralaboratory means.

CERTIFIED VALUES

	%Fe	%Si	%Ca	%Mg	%Al	%Ti	%Mn	%P	%S	%Na	%K	%F	%V	%Cr	%Ni	%C
M_M	33·21	8·32	2·80	0·89	5·62	0·29	0·22	0·88	0·103	0·068	0·49	0·19	0·077	0·041	0·016	1·80
s_M	0·13	0·08	0·10	0·02	0·10	0·01	0·01	0·02	0·006	0·008	0·01	0·01	0·004	0·002	0·001	0·04

All values are 'total' element content unless otherwise stated

*The attention of users is drawn to the hygroscopic nature of the sample

BAS

BUREAU OF ANALYSED SAMPLES LIMITED

Newham Hall, Middlesbrough, England. DECEMBER, 1976

(Reprinted October 1979)

4.4d: Swedish Slag

Appendix 4.5: Certified and recommended values of the SEM reference materials for the slags
4.5a: BCR-2 Basalt Columbia River

4.5b: BIR-1 Icelandic basalt

4.5c: BHVO-2 Basalt Hawaiian volcanic observatory

Appendix 4.6: BAS 1/19 Low phosphorous iron

Appendix 4.7: Chronology of the study sites

Area	**Relative Age**	**Site Name**	**C^{14} Date**
Ufipa	Recent	Pito ward sites	1850-1950 AD
Unyiha	Recent*	Itaka and Kapele ward sites	-
Umatengo	Ancient	Ntuha site	Mid 1st Millennium AD
	Recent*	Kigonsera sites	-
Uhehe	Ancient	Magubike 1	Mid 2nd Millennium AD
	Recent*	Magubike 2 and Ngongwa sites	-
Ubena	Recent*	Njombe sites	-

*Archaeologically visible furnaces can date to the 19th or 20th century (*cf*. Davison and Mosley 1988: 74).

Appendix 5: Chapter 5 Appendices

Appendix 5.1: List of smelting (SE) and refining (RF) sites from Mkumbi sub-village. Note DWS=distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 04.325'), E (31^0 40.8')	240	452	1912	Imamu Khasimu
2	SE3	S (8^0 04.302'), E (31^0 40.879')	240	79	1914	Faraja Mgimba
3	SE4	S (8^0 04.305'), E (31^0 40.826')	260	408	1917	Pamela Felix
4	SE7	S (8^0 04.286'), E (31^0 40.808')	283	314	1921	Amne Kassam
5	SE10	S (8^0 04.455'), E (31^0 40.786')	190	201	1899	George Samweli
6	SE11	S (8^0 04.048'), E (31^0 41.021')	106	254	1920	Mzee Meneja
7	SE12	S (8^0 04.071'), E (31^0 41.068')	53	201	1917	Reuben Tembo
8	RF2	S (8^0 04.326'), E (31^0 40.884')	190	804	1908	George Samweli
9	RF5A/B	S (8^0 04.313'), E (31^0 40.834')	260	55	1919	Anita Msaki
10	RF6	S (8^0 04.319'), E (31^0 40.795')	270	50	1918	Pamela Felix
11	RF8	S (8^0 04.259'), E (31^0 40.826')	283	201	1923	Emmanuel Josiah
12	RF9	S (8^0 04.237'), E (31^0 40.827')	283	254	1922	Furgency John
13	RF13A	S (8^0 04.373'), E (31^0 40.807')	213	13	1911	Bahati Juma
14	RF13B	S (8^0 04.375'), E (31^0 40.808')	212	13	1914	Hilda Missingo
15	**Average (SE)**		**196**	**273**	**1914**	
16	**Average (RF)**		**244**	**199**	**1916**	

Appendix 5.2: List of smelting (SE), refining (RF), and smithing (ST) sites from Chulu sub-village. Note DWS=distance to the nearest water source, and MLB=Malimbo sites

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 04.105'), E (31^0 41.433')	230	201	1936	Gabriel Kaminyoge
2	SE2	S (8^0 04.061'), E (31^0 41.422')	240	154	1936	Furgency John
3	SE3	S (8^0 04.062'), E (31^0 41.399')	240	346	1935	Abdu Slim
4	SE4	S (8^0 04.084'), E (31^0 41.468')	230	346	1936	Emmanuel Josiah
5	SE5	S (8^0 04.124'), E (31^0 41.621')	200	201	1931	George Samweli
6	SE6	S (8^0 04.211'), E (31^0 41.544')	200	45	1931	Emmanuel Josiah
7	SE7	S (8^0 04.207'), E (31^0 41.570')	224	141	1933	Noel Ng'itu
8	SE8	S (8^0 04.099'), E (31^0 41.654')	235	314	1950	Mzee Meneja
9	MLBRF9	S (8^0 04.690'), E (31^0 41.230')	250	359	1912	Mzee Meneja
10	MLBST10	S (8^0 04.684'), E (31^0 41.128')	250	79	1905	Mzee Meneja
11	**Average (SE)**		**225**	**219**	**1936**	

Appendix 5.3: List of smelting (SE) and refining (RF) sites from Kamafupa sub-village. Note DWS=distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 04.462'), E (31^0 38.827')	218	804	1902	Mzee Meneja
2	SE2	S (8^0 04.499'), E (31^0 38.795')	218	907	1905	Edwinus Lyaya
3	SE10	S (8^0 04.803'), E (31^0 38.526')	67	1256	1939	Mzee Meneja
4	SE11	S (8^0 04.715'), E (31^0 38.869')	233	201	1890	Edwinus Lyaya
5	SE12	S (8^0 04.676'), E (31^0 38.832')	233	191	1922	Reuben Tembo
6	SE13	S (8^0 04.672'), E (31^0 38.745')	233	227	1925	Edwinus Lyaya
7	SE14	S (8^0 04.667'), E (31^0 38.666')	130	201	1922	Anita Msaki
8	SE15	S (8^0 04.699'), E (31^0 38.638')	130	177	1928	Mzee Meneja
9	SE16	S (8^0 04.777'), E (31^0 38.582')	67	531	1936	Aldah Barghash
10	SE17	S (8^0 04.783'), E (31^0 38.541')	67	172	1935	Abdu Slim
11	RF3	S (8^0 04.533'), E (31^0 38.596')	130	64	1920	Mzee Meneja
12	RF4	S (8^0 04.566'), E (31^0 38.549')	130	154	1923	Noel Ng'itu
13	RF5	S (8^0 04.576'), E (31^0 38.512')	200	216	1921	Salum Muya
14	RF6	S (8^0 04.600'), E (31^0 38.490')	167	113	1923	Lioba Justine
15	RF7	S (8^0 04.582'), E (31^0 38.462')	200	113	1930	Sigfrid Kikoti
16	RF8	S (8^0 04.681'), E (31^0 38.447')	200	201	1925	Abdu Slim
17	RF9	S (8^0 04.745'), E (31^0 38.475')	130	145	1923	Faraja Mgimba
18	**Average (SE)**		**160**	**467**	**1920**	
19	**Average (RF)**		**165**	**144**	**1924**	

Appendix 5.4: List of smelting (SE) and refining (RF) sites from Nangesu sub-village. Note DWS=distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE5	S (8^0 04.988'), E (31^0 38.006')	150	401	1906	Noel Ng'itu
2	SE6	S (8^0 05.019'), E (31^0 38.948')	120	206	1908	Mzee Meneja
3	SE8	S (8^0 05.000'), E (31^0 38.895')	123	401	1915	Abdu Slim
4	SE12	S (8^0 04.981'), E (31^0 38.737')	135	232	1933	Noel Ng'itu
5	RF1	S (8^0 04.942'), E (31^0 38.815')	100	660	1929	David Samwel
6	RF2	S (8^0 04.981'), E (31^0 38.810')	119	660	1926	Noel Ng'itu
7	RF3	S (8^0 04.886'), E (31^0 38.826')	111	113	1926	Edwinus Lyaya
8	RF4	S (8^0 04.883'), E (31^0 38.781')	98	222	1933	Edwinus Lyaya
9	RF7	S (8^0 04.998'), E (31^0 38.929')	98	272	1913	Tumsifu Usiri
10	RF9	S (8^0 05.006'), E (31^0 38.868')	105	222	1915	Vincent Charles
11	RF10	S (8^0 04.960'), E (31^0 38.909')	120	437	1918	Mzee Meneja
12	RF11	S (8^0 04.909'), E (31^0 38.699')	120	238	1939	Furgency John
13	RF13	S (8^0 04.963'), E (31^0 38.763')	148	186	1932	Furgency John
14	**Average (SE)**		**132**	**310**	**1915**	
15	**Average (RF)**		**113**	**334**	**1926**	

Appendix 5.5: List of smelting (SE), refining (RF), smithing (ST), and Ore sites from Nantula sub-village. Note NKL=Nkale, LPF=Lupofwe, and WZL=wanzale areas, and DWS=distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 05.836'), E (31^0 40.605')	210	201	1904	Yusta Komba
2	SE3	S (8^0 05.950'), E (31^0 40.783')	180	85	1899	Imamu Khasimu
3	SE4	S (8^0 05.898'), E (31^0 40.827')	175	216	1889	Diana Mrisho
4	SE5	S (8^0 05.911'), E (31^0 40.852')	150	88	1888	Sakina Mgaya
5	SE6	S (8^0 06.008'), E (31^0 40.839')	130	113	1897	Gillan Orenge
6	SE7	S (8^0 06.057'), E (31^0 40.646')	130	314	1916	Catherine Letara
7	SE8	S (8^0 06.061'), E (31^0 40.732')	100	531	1912	Amne Kassam
8	SE10	S (8^0 06.140'), E (31^0 40.949')	100	314	1894	Aldah Barghash
9	NKLSE12	S (8^0 06.477'), E (31^0 41.176')	65	133	1912	Winifrida Deo
10	NKLSE13	S (8^0 06.498'), E (31^0 41.168')	65	452	1913	Abdu Slim
11	RF2	S (8^0 05.917'), E (31^0 40.775')	60	79	1897	Elieth Frednard
12	RF9	S (8^0 06.135'), E (31^0 40.929')	70	79	1896	Edwinus Lyaya
13	RF11	S (8^0 06.114'), E (31^0 40.943')	70	314	1893	Abdu Slim
14	LPFST14	S (8^0 06.184'), E (31^0 41.127')	100	79	1895	Mzee Meneja
15	WZLOre1	S (8^0 06.540'), E (31^0 40.081')	140	1809	1883	Mzee Meneja
16	**Average (SE)**		**131**	**245**	**1902**	
17	**Average (RF)**		**67**	**157**	**1895**	

Appendix 5.6: List of smelting (SE), refining (RF), and Ore sites from Tupa sub-village. Note DWS=distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE2	S (8^0 06.493'), E (31^0 41.540')	300	154	1921	Tumsifu Usiri
2	SE3	S (8^0 06.491'), E (31^0 41.576')	300	28	1936	David Samwel
3	SE4	S (8^0 06.576'), E (31^0 41.597')	300	227	1927	Reuben Tembo
4	SE5	S (8^0 06.602'), E (31^0 41.649')	250	834	1932	David Samwel
5	SE6	S (8^0 06.628'), E (31^0 41.620')	240	452	1932	Reuben Tembo
6	SE12	S (8^0 06.595'), E (31^0 41.668')	250	283	1929	Aldah Barghash
7	SE15	S (8^0 06.713'), E (31^0 41.801')	250	707	1940	David Samwel
8	SE16	S (8^0 06.687'), E (31^0 41.815')	250	113	1940	David Samwel

9	SE17	S (8^0 06.577'), E (31^0 41.528')	250	177	1937	Charles Maganga
10	SE18	S (8^0 06.582'), E (31^0 41.509')	250	113	1938	Gabriel Kaminyoge
11	SE19	S (8^0 06.180'), E (31^0 41.260')	250	95	1827	Furgency John
12	SE21	S (8^0 06.217'), E (31^0 41.265')	250	1134	1900	Furgency John
13	SE24	S (8^0 06.233'), E (31^0 41.240')	200	201	1907	Liberatus Costantine
14	SE26	S (8^0 06.251'), E (31^0 41.285')	250	804	1906	Noel Ng'itu
15	SE27	S (8^0 06.217'), E (31^0 41.437')	250	314	1906	David Samwel
16	SE28	S (8^0 06.377'), E (31^0 41.437')	250	1017	1921	Tumsifu Usiri
17	SE29	S (8^0 06.406'), E (31^0 41.310')	250	314	1914	Winifrida Deo
18	SE30	S (8^0 06.633'), E (31^0 41.824')	500	452	1932	David Samwel
19	SE31	S (8^0 06.670'), E (31^0 41.840')	450	327	1938	Gabriel Kaminyoge
20	SE32	S (8^0 06.686'), E (31^0 41.865')	400	64	1939	Florentina Bernard
21	SE33	S (8^0 06.692'), E (31^0 41.884')	300	804	1941	Lioba Jastin
22	SE34	S (8^0 06.632'), E (31^0 41.875')	400	266	1941	Florentina Bernard
23	SE35	S (8^0 06.660'), E (31^0 41.956')	400	121	1950	Florentina Bernard
24	SE36	S (8^0 06.620'), E (31^0 41.902')	395	380	1914	Gabriel Kaminyoge
25	SE37	S (8^0 06.598'), E (31^0 41.912')	420	211	1948	Florentina Bernard
26	SE38	S (8^0 06.602'), E (31^0 41.841')	400	254	1942	David Samwel
27	SE39	S (8^0 06.587'), E (31^0 41.818')	400	314	1939	David Samwel
28	SE40	S (8^0 06.551'), E (31^0 41.801')	400	333	1938	David Samwel
29	SE41	S (8^0 06.529'), E (31^0 41.797')	450	380	1936	David Samwel
30	SE43	S (8^0 06.550'), E (31^0 41.860')	450	154	1944	David Samwel
31	SE46	S (8^0 06.481'), E (31^0 41.906')	500	283	1953	Florentina Bernard
32	SE47	S (8^0 06.474'), E (31^0 41.923')	500	95	1957	Gabriel Kaminyoge
33	SE48	S (8^0 06.445'), E (31^0 41.934')	300	452	1958	Gabriel Kaminyoge
34	Ore50	S (8^0 06.386'), E (31^0 41.548')	300	907	1919	Mzee Meneja
35	RF1	S (8^0 06.466'), E (31^0 41.561')	300	615	1922	Edwinus Lyaya
36	RF7	S (8^0 06.547'), E (31^0 41.638')	300	113	1923	Reuben Tembo
37	RF8	S (8^0 06.551'), E (31^0 41.648')	300	1075	1925	Reuben Tembo
38	RF9	S (8^0 06.535'), E (31^0 41.583')	300	61	1920	David Samwel
39	RF10	S (8^0 06.515'), E (31^0 41.590')	250	346	1919	Edwinus Lyaya
40	RF11	S (8^0 06.585'), E (31^0 41.647')	300	133	1925	Aldah Barghash
41	RF13	S (8^0 06.649'), E (31^0 41.690')	300	133	1932	Anita Msaki
42	RF14	S (8^0 06.616'), E (31^0 41.702')	300	615	1929	Anita Msaki
43	RF20	S (8^0 06.190'), E (31^0 41.236')	250	113	1885	Frida Kombe
44	RF22	S (8^0 06.211'), E (31^0 41.286')	250	113	1901	Furgency John
45	RF23	S (8^0 06.617'), E (31^0 41.218')	250	113	1899	Emmanuel Josiah
46	RF25	S (8^0 06.227'), E (31^0 41.351')	250	154	1904	Charles Maganga
47	RF42	S (8^0 06.540'), E (31^0 41.830')	450	154	1941	David Samwel
48	RF44	S (8^0 06.517'), E (31^0 41.835')	400	79	1943	Sigfrid Kikoti

49	RF45	S (8^0 06.488'), E (31^0 41.880')	400	380	1949	Gabriel Kaminyoge
50	RF49	S (8^0 06.423'), E (31^0 41.788')	300	201	1943	Mzee Meneja
51	RF51	S (8^0 06.475'), E (31^0 41.536')	300	500	1927	Edwinus Lyaya
52	**Average (SE)**		**333**	**359**	**1930**	
53	**Average (RF)**		**306**	**288**	**1923**	

Appendix 5.7: Full results of the (P) XRF-EDS major and minor element concentrations of the technical ceramics from Mkumbi smelting 3 and refining 2 sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyères, and TBs=test briquettes

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMkumbi2 FW1	1.16	1.33	28.86	64.46	0.07	0.03	1.21	0.17	0.80	0.02	0.02	0.08	4.72	103
TzMkumbi2 FW1_r01	0.74	1.36	29.27	64.38	0.07	0.03	1.23	0.17	0.79	0.01	0.02	0.08	4.76	103
TzMkumbi2 FW1_r02	0.79	1.28	29.16	64.53	0.07	0.04	1.20	0.17	0.81	0.01	0.02	0.08	4.75	103
Average	0.90	1.32	29.10	64.46	0.07	0.03	1.21	0.17	0.80	0.01	0.02	0.08	4.74	103
TzMkumbi2 FW2	1.08	1.24	27.41	66.19	0.08	0.03	1.19	0.17	0.77	0.01	0.02	0.09	4.64	103
TzMkumbi2 FW2_r01	0.72	1.32	27.50	66.34	0.11	0.03	1.18	0.18	0.77	0.01	0.02	0.09	4.65	103
TzMkumbi2 FW2_r02	0.77	1.20	27.53	66.35	0.10	0.04	1.19	0.17	0.78	0.01	0.02	0.09	4.68	103
Average	0.86	1.25	27.48	66.29	0.10	0.03	1.19	0.17	0.77	0.01	0.02	0.09	4.66	103
TzMkumbi2 FW3	0.72	1.31	28.16	65.48	0.10	0.03	1.21	0.17	0.80	0.01	0.02	0.07	4.83	103
TzMkumbi2 FW3_r01	0.74	1.29	28.05	65.58	0.07	0.04	1.23	0.17	0.80	0.01	0.02	0.07	4.83	103
TzMkumbi2 FW3_r02	0.52	1.35	28.10	65.66	0.10	0.04	1.23	0.17	0.81	0.01	0.02	0.07	4.83	103
Average	0.66	1.32	28.10	65.57	0.09	0.04	1.22	0.17	0.80	0.01	0.02	0.07	4.83	103
TzMkumbi2 TB1	1.16	0.74	16.11	79.66	0.09	0.02	1.17	0.13	0.58	0.01	0.02	0.05	3.18	103
TzMkumbi2 TB1_r01	1.60	0.83	16.03	79.26	0.09	0.02	1.17	0.13	0.59	0.01	0.02	0.05	3.15	103
TzMkumbi2 TB1_r02	1.35	0.73	16.10	79.52	0.08	0.02	1.18	0.13	0.59	0.01	0.02	0.05	3.16	103
Average	1.37	0.77	16.08	79.48	0.09	0.02	1.17	0.13	0.59	0.01	0.02	0.05	3.16	103
TzMkumbi2 TB2	0.93	0.86	20.36	74.67	0.10	0.03	1.19	0.16	0.70	0.01	0.03	0.05	3.83	103
TzMkumbi2 TB2_r01	1.42	0.76	20.32	74.37	0.07	0.02	1.18	0.17	0.69	0.01	0.03	0.05	3.82	103
TzMkumbi2 TB2_r02	1.37	0.82	20.30	74.35	0.10	0.03	1.17	0.17	0.70	0.01	0.03	0.05	3.82	103
Average	1.24	0.81	20.33	74.46	0.09	0.03	1.18	0.17	0.70	0.01	0.03	0.05	3.82	103
TzMkumbi2 TB3	1.14	0.83	19.20	75.65	0.09	0.02	1.16	0.13	0.67	0.01	0.02	0.05	3.93	103
TzMkumbi2 TB3_r01	0.88	0.86	19.31	75.76	0.10	0.02	1.16	0.13	0.67	0.01	0.02	0.05	3.94	103
TzMkumbi2 TB3_r02	1.14	0.84	19.30	75.57	0.09	0.02	1.14	0.14	0.66	0.01	0.02	0.05	3.93	103
Average	1.05	0.84	19.27	75.66	0.09	0.02	1.15	0.14	0.67	0.01	0.02	0.05	3.93	103

TzMkumbi2 TYR1	0.75	1.02	30.28	63.92	0.09	0.02	0.87	0.20	0.86	0.01	0.02	0.08	4.80	103
TzMkumbi2 TYR1_r01	0.71	1.08	30.23	63.91	0.12	0.03	0.85	0.20	0.88	0.02	0.02	0.08	4.79	103
TzMkumbi2 TYR1_r02	0.79	0.98	30.17	64.03	0.12	0.03	0.88	0.20	0.85	0.01	0.02	0.08	4.78	103
Average	0.75	1.03	30.23	63.95	0.11	0.03	0.86	0.20	0.86	0.01	0.02	0.08	4.79	103
TzMkumbi2 TYR2	0.58	1.14	29.75	64.61	0.11	0.02	0.82	0.25	0.83	0.01	0.02	0.08	4.70	103
TzMkumbi2 TYR2_r01	0.74	1.15	29.56	64.67	0.09	0.02	0.81	0.24	0.83	0.00	0.03	0.08	4.70	103
TzMkumbi2 TYR2_r02	0.95	1.16	29.53	64.46	0.09	0.03	0.82	0.24	0.82	0.01	0.03	0.08	4.70	103
Average	0.76	1.15	29.61	64.58	0.10	0.02	0.82	0.24	0.83	0.01	0.02	0.08	4.70	103
TzMkumbi2 TYR3	0.79	1.09	29.03	64.96	0.12	0.02	0.88	0.27	0.85	0.01	0.02	0.08	4.81	103
TzMkumbi2 TYR3_r01	0.66	1.17	28.94	65.08	0.13	0.03	0.87	0.27	0.85	0.01	0.02	0.08	4.81	103
TzMkumbi2 TYR3_r02	1.25	1.14	28.89	64.66	0.13	0.03	0.84	0.27	0.84	0.01	0.02	0.08	4.77	103
Average	0.90	1.13	28.95	64.90	0.13	0.02	0.86	0.27	0.85	0.01	0.02	0.08	4.79	103
TzMkumbi3 FW1	1.29	0.98	24.63	69.67	0.09	0.02	1.07	0.18	0.74	0.01	0.03	0.06	4.15	103
TzMkumbi3 FW1_r01	1.06	0.96	24.53	69.99	0.09	0.02	1.04	0.18	0.74	0.01	0.03	0.06	4.19	103
TzMkumbi3 FW1_r02	1.22	0.97	24.57	69.79	0.07	0.02	1.06	0.18	0.75	0.01	0.03	0.06	4.19	103
Average	1.19	0.97	24.58	69.82	0.08	0.02	1.06	0.18	0.74	0.01	0.03	0.06	4.18	103
TzMkumbi3 FW2	0.91	0.92	25.97	68.83	0.06	0.03	1.04	0.18	0.73	0.02	0.02	0.06	4.15	103
TzMkumbi3 FW2_r01	0.74	0.90	26.06	68.88	0.09	0.03	1.04	0.19	0.74	0.01	0.02	0.07	4.15	103
TzMkumbi3 FW2_r02	0.84	1.03	25.91	68.82	0.09	0.03	1.04	0.18	0.73	0.01	0.02	0.06	4.15	103
Average	0.83	0.95	25.98	68.84	0.08	0.03	1.04	0.18	0.73	0.01	0.02	0.06	4.15	103
TzMkumbi3 FW3	0.87	1.09	26.78	67.74	0.06	0.04	1.15	0.16	0.73	0.02	0.02	0.06	4.20	103
TzMkumbi3 FW3_r01	1.28	1.09	26.64	67.46	0.09	0.04	1.14	0.16	0.74	0.01	0.02	0.06	4.20	103
TzMkumbi3 FW3_r02	0.89	0.99	26.95	67.59	0.09	0.04	1.18	0.15	0.73	0.01	0.02	0.06	4.22	103
Average	1.01	1.06	26.79	67.60	0.08	0.04	1.16	0.16	0.74	0.01	0.02	0.06	4.21	103
TzMkumbi3 TB1	0.90	0.65	16.79	79.52	0.09	0.02	0.93	0.11	0.62	0.01	0.03	0.04	3.24	103
TzMkumbi3 TB1_r01	1.39	0.70	16.79	79.05	0.07	0.02	0.92	0.10	0.61	0.01	0.02	0.04	3.21	103
TzMkumbi3 TB1_r02	1.33	0.69	16.66	79.20	0.09	0.02	0.93	0.10	0.61	0.01	0.02	0.04	3.23	103
Average	1.21	0.68	16.75	79.26	0.08	0.02	0.92	0.10	0.61	0.01	0.02	0.04	3.22	103
TzMkumbi3 TB2	1.23	0.55	13.74	82.91	0.09	0.02	0.80	0.09	0.53	0.01	0.02	0.04	2.90	103
TzMkumbi3 TB2_r01	1.33	0.52	13.82	82.74	0.08	0.02	0.81	0.09	0.54	0.01	0.02	0.04	2.90	103
TzMkumbi3 TB2_r02	1.44	0.51	13.75	82.73	0.09	0.02	0.82	0.09	0.54	0.01	0.02	0.04	2.89	103

Average	1.33	0.53	13.77	82.79	0.09	0.02	0.81	0.09	0.54	0.01	0.02	0.04	2.89	103
TzMkumbi3 TB3	1.66	0.47	14.13	81.96	0.07	0.02	0.84	0.15	0.55	0.01	0.03	0.04	3.02	103
TzMkumbi3 TB3_r01	1.27	0.53	14.19	82.16	0.09	0.02	0.87	0.15	0.56	0.01	0.03	0.04	3.03	103
TzMkumbi3 TB3_r02	1.14	0.55	14.10	82.35	0.09	0.02	0.86	0.15	0.55	0.01	0.03	0.04	3.05	103
Average	1.36	0.52	14.14	82.16	0.08	0.02	0.86	0.15	0.55	0.01	0.03	0.04	3.03	103
TzMkumbi3 TYR1	0.91	1.28	29.77	63.37	0.08	0.03	1.05	0.42	0.85	0.01	0.02	0.09	5.04	103
TzMkumbi3 TYR1_r01	0.76	1.44	29.78	63.27	0.12	0.03	1.06	0.43	0.84	0.02	0.02	0.09	5.06	103
TzMkumbi3 TYR1_r02	0.69	1.28	29.91	63.38	0.12	0.04	1.04	0.43	0.84	0.01	0.02	0.09	5.07	103
Average	0.79	1.33	29.82	63.34	0.11	0.03	1.05	0.43	0.84	0.01	0.02	0.09	5.06	103
TzMkumbi3 TYR2	0.76	1.36	26.16	68.02	0.07	0.02	1.06	0.37	0.79	0.01	0.03	0.08	4.19	103
TzMkumbi3 TYR2_r01	0.94	1.45	26.10	67.86	0.10	0.01	1.06	0.36	0.77	0.01	0.03	0.08	4.15	103
TzMkumbi3 TYR2_r02	0.94	1.43	26.05	67.91	0.10	0.02	1.08	0.35	0.76	0.01	0.03	0.08	4.16	103
Average	0.88	1.42	26.10	67.93	0.09	0.02	1.06	0.36	0.77	0.01	0.03	0.08	4.16	103
TzMkumbi3 TYR3	0.81	1.32	29.92	63.77	0.09	0.02	1.02	0.40	0.82	0.01	0.02	0.09	4.63	103
TzMkumbi3 TYR3_r01	0.74	1.32	29.90	63.81	0.09	0.03	1.03	0.40	0.83	0.01	0.02	0.08	4.65	103
TzMkumbi3 TYR3_r02	1.16	1.30	29.77	63.54	0.12	0.03	1.04	0.41	0.82	0.01	0.02	0.08	4.61	103
Average	0.90	1.31	29.86	63.71	0.10	0.03	1.03	0.40	0.83	0.01	0.02	0.08	4.63	103

***Appendix 5.8*:** Full results of the (P) XRF-EDS trace element concentrations (in ppm) of the technical ceramics from Mkumbi smelting 3 and refining 2 sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyères, and TBs=test briquettes

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	WO3	PbO	Th
TzMkumbi2 FW1	94	26	54	48	13	49	33	28	268	14	114	27	51	12	8	16	19
TzMkumbi2 FW1_r01	72	38	52	49	13	49	33	28	261	13	115	28	51	11	21	15	19
TzMkumbi2 FW1_r02	75	26	52	46	12	50	34	28	263	14	114	24	48	12	6	16	19
Average	80	30	53	48	13	49	33	28	264	14	114	26	50	11	12	16	19
TzMkumbi2 FW2	68	29	41	45	13	45	34	28	258	14	115	24	58	11	25	21	19
TzMkumbi2 FW2_r01	58	30	41	49	12	45	34	28	250	15	118	27	59	10	28	20	20
TzMkumbi2 FW2_r02	75	31	39	49	13	45	34	28	258	16	118	26	57	8	27	20	19
Average	67	30	40	48	13	45	34	28	255	15	117	26	58	10	27	20	19
TzMkumbi2 FW3	50	37	48	52	13	49	34	28	269	15	120	27	49	12	31	17	19
TzMkumbi2 FW3_r01	51	33	52	49	14	49	35	28	263	11	119	25	49	9	25	17	20
TzMkumbi2 FW3_r02	67	30	47	47	13	48	34	28	273	14	119	28	53	9	26	17	20
Average	56	33	49	50	13	49	34	28	268	13	120	27	50	10	27	17	20
TzMkumbi2 TB1	44	20	41	34	8	36	27	22	231	7	87	21	45	9	47	40	18
TzMkumbi2 TB1_r01	51	16	38	36	8	35	27	21	235	11	88	23	45	11	47	39	18
TzMkumbi2 TB1_r02	60	16	38	32	8	35	26	22	228	8	89	21	44	9	43	38	18
Average	52	17	39	34	8	35	27	22	231	9	88	22	45	9	45	39	18
TzMkumbi2 TB2	48	21	46	37	10	39	26	23	267	12	89	25	49	11	30	90	21
TzMkumbi2 TB2_r01	40	21	45	38	10	38	26	24	266	12	90	25	48	12	33	92	20
TzMkumbi2 TB2_r02	48	20	47	38	9	39	26	24	263	12	89	25	50	10	21	92	20
Average	45	21	46	38	9	38	26	24	265	12	89	25	49	11	28	91	20
TzMkumbi2 TB3	57	19	46	37	9	40	26	23	227	12	91	21	46	8	54	92	18
TzMkumbi2 TB3_r01	59	22	48	37	9	40	26	23	229	12	91	22	46	11	63	91	18
TzMkumbi2 TB3_r02	55	24	47	36	9	41	25	23	232	10	89	23	47	11	65	92	17

Average	57	22	47	37	9	40	26	23	229	11	90	22	46	10	61	92	17
TzMkumbi2 TYR1	62	30	51	56	13	42	27	30	221	18	98	27	43	8	31	14	18
TzMkumbi2 TYR1_r01	88	31	54	55	13	41	27	30	223	17	97	27	43	8	32	15	17
TzMkumbi2 TYR1_r02	82	27	50	58	13	42	27	29	218	17	98	28	43	10	22	15	18
Average	77	29	52	56	13	42	27	30	221	17	98	28	43	9	28	14	17
TzMkumbi2 TYR2	85	30	52	55	14	41	27	29	212	17	91	25	41	10	48	14	16
TzMkumbi2 TYR2_r01	79	33	49	54	13	42	27	30	217	16	93	25	40	11	54	15	18
TzMkumbi2 TYR2_r02	87	27	47	54	12	41	27	29	218	15	92	25	41	10	53	14	16
Average	83	30	49	54	13	41	27	29	216	16	92	25	41	10	51	14	17
TzMkumbi2 TYR3	86	35	50	68	14	44	29	28	210	15	96	27	43	8	53	13	18
TzMkumbi2 TYR3_r01	101	24	50	67	14	42	30	28	207	17	96	26	45	6	40	14	17
TzMkumbi2 TYR3_r02	70	31	52	67	14	43	29	29	207	18	99	30	45	8	42	14	18
Average	86	30	50	67	14	43	29	28	208	17	97	28	44	7	45	14	18
TzMkumbi3 FW1	52	24	34	47	11	39	25	21	220	15	86	19	42	11	70	32	17
TzMkumbi3 FW1_r01	53	25	37	47	12	40	25	21	215	15	88	19	44	10	72	33	19
TzMkumbi3 FW1_r02	61	20	39	48	12	40	26	21	221	16	89	20	45	6	69	33	18
Average	55	23	37	47	11	40	25	21	219	15	88	19	44	9	70	33	18
TzMkumbi3 FW2	61	28	50	37	12	40	25	26	237	16	89	19	45	10	78	21	18
TzMkumbi3 FW2_r01	59	25	50	39	11	41	26	26	230	15	88	19	47	9	69	21	18
TzMkumbi3 FW2_r02	61	26	52	37	11	41	25	26	234	13	91	21	47	9	66	21	17
Average	60	26	51	38	12	41	25	26	234	15	89	20	47	9	71	21	17
TzMkumbi3 FW3	58	29	45	40	13	42	26	23	249	15	87	19	46	9	33	17	18
TzMkumbi3 FW3_r01	51	26	47	39	11	42	26	22	247	15	86	17	46	8	32	18	18
TzMkumbi3 FW3_r02	48	29	45	41	11	42	26	22	246	14	87	18	44	10	36	18	19
Average	52	28	46	40	11	42	26	22	247	14	87	18	45	9	34	17	19
TzMkumbi3 TB1	48	14	42	34	9	32	22	21	258	11	78	21	42	11	112	19	18
TzMkumbi3 TB1_r01	60	15	41	34	8	32	22	21	251	10	75	20	41	10	113	19	18
TzMkumbi3 TB1_r02	50	19	46	33	9	32	22	21	251	12	74	19	43	11	116	19	18
Average	53	16	43	34	9	32	22	21	253	11	76	20	42	11	113	19	18
TzMkumbi3 TB2	54	12	18	27	7	28	20	21	237	10	67	23	42	12	136	26	19
TzMkumbi3 TB2_r01	51	13	19	28	6	28	20	21	225	9	63	20	39	11	137	25	18

TzMkumbi3 TB2_r02	37	16	20	29	8	28	20	21	227	9	65	19	40	12	143	25	19
Average	47	14	19	28	7	28	20	21	229	10	65	20	41	12	139	25	18
TzMkumbi3 TB3	47	15	21	29	7	27	22	22	264	10	68	21	44	11	100	23	20
TzMkumbi3 TB3_r01	36	10	21	28	6	26	22	22	270	9	68	23	46	14	106	23	19
TzMkumbi3 TB3_r02	38	15	20	30	7	26	22	22	274	10	67	20	48	9	107	23	19
Average	41	13	21	29	7	26	22	22	270	9	68	21	46	11	104	23	19
TzMkumbi3 TYR1	98	27	45	57	14	47	45	31	227	16	108	30	50	8	64	15	19
TzMkumbi3 TYR1_r01	87	34	47	57	14	47	45	31	232	17	110	27	49	8	60	15	18
TzMkumbi3 TYR1_r02	79	33	47	56	13	47	44	31	233	18	112	28	47	9	65	16	18
Average	88	31	46	56	14	47	44	31	231	17	110	28	49	8	63	15	18
TzMkumbi3 TYR2	73	31	52	45	12	47	37	27	228	15	96	26	48	8	112	16	19
TzMkumbi3 TYR2_r01	65	29	55	45	11	47	37	27	231	15	96	26	46	8	110	15	18
TzMkumbi3 TYR2_r02	58	32	54	43	13	46	36	27	227	14	96	29	46	9	109	15	19
Average	65	31	54	44	12	47	37	27	228	15	96	27	46	8	110	15	18
TzMkumbi3 TYR3	76	33	45	59	14	46	42	30	231	14	109	27	47	9	50	16	18
TzMkumbi3 TYR3_r01	76	30	46	56	13	46	42	29	229	17	110	29	48	8	49	15	18
TzMkumbi3 TYR3_r02	88	34	45	56	15	46	42	30	226	15	111	27	44	8	57	16	19
Average	80	32	46	57	14	46	42	30	229	15	110	28	46	8	52	15	18

Appendix 5.9: correction factors used to proportionally adjust the mol weight of oxides in relation to the mol weight of FeO. Note the mol weight of FeO=71.84 g/mol.

Oxides	Mol weight (g/mol)	Correction factor
Na_2O	61.98	1.16
MgO	40.30	1.78
CaO	56.08	1.28
K_2O	94.20	0.76
TiO_2	79.87	0.89
MnO	70.93	1.01
ZrO_2	123.22	0.58

Appendix 5.10: Full results of the (P) XRF-EDS major and minor element concentrations of the technical ceramics from Mkumbi smelting 4 and refining 5B sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and TBs=test briquettes

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMkumbi4 FW1	0.74	1.59	32.77	59.23	0.16	0.02	1.26	1.09	0.90	0.02	0.02	0.11	5.00	103
TzMkumbi4 FW1_r01	0.59	1.46	32.81	59.40	0.16	0.03	1.24	1.10	0.92	0.02	0.02	0.11	5.05	103
Average	0.67	1.52	32.79	59.32	0.16	0.02	1.25	1.09	0.91	0.02	0.02	0.11	5.03	103
TzMkumbi4 FW2	0.38	1.32	29.97	62.99	0.14	0.02	1.76	0.70	0.83	0.01	0.02	0.10	4.66	103
TzMkumbi4 FW2_r01	0.96	1.29	29.78	62.72	0.10	0.03	1.77	0.71	0.82	0.02	0.02	0.10	4.61	103
Average	0.67	1.31	29.88	62.86	0.12	0.03	1.76	0.70	0.82	0.02	0.02	0.10	4.64	103
TzMkumbi4 FW3	0.94	1.40	30.40	61.20	0.13	0.02	1.91	0.96	0.87	0.01	0.02	0.10	4.93	103
TzMkumbi4 FW3_r01	0.66	1.46	30.35	61.46	0.14	0.01	1.91	0.96	0.89	0.01	0.02	0.10	4.94	103
Average	0.80	1.43	30.38	61.33	0.14	0.01	1.91	0.96	0.88	0.01	0.02	0.10	4.93	103
TzMkumbi4 TB1	0.75	1.07	25.95	67.92	0.11	0.02	0.94	0.45	0.88	0.02	0.02	0.08	4.69	103
TzMkumbi4 TB1_r01	0.92	0.95	26.11	67.76	0.11	0.02	0.95	0.46	0.86	0.02	0.02	0.08	4.63	103
Average	0.84	1.01	26.03	67.84	0.11	0.02	0.94	0.46	0.87	0.02	0.02	0.08	4.66	103
TzMkumbi4 TB2	1.26	0.88	23.70	70.39	0.11	0.03	0.92	0.25	0.80	0.02	0.03	0.08	4.42	103
TzMkumbi4 TB2_r01	1.21	0.82	23.76	70.43	0.11	0.02	0.90	0.25	0.82	0.01	0.03	0.08	4.44	103
Average	1.24	0.85	23.73	70.41	0.11	0.03	0.91	0.25	0.81	0.01	0.03	0.08	4.43	103
TzMkumbi4 TB3	0.96	0.89	26.79	66.63	0.09	0.02	0.89	0.20	0.90	0.02	0.02	0.10	5.37	103
TzMkumbi4 TB3_r01	0.96	1.00	26.72	66.58	0.12	0.02	0.89	0.21	0.90	0.01	0.02	0.10	5.37	103
Average	0.96	0.94	26.76	66.61	0.10	0.02	0.89	0.21	0.90	0.02	0.02	0.10	5.37	103
TzMkumbi4 TYR1	1.05	1.01	23.90	69.54	0.13	0.01	0.87	0.68	0.86	0.02	0.03	0.09	4.72	103

TzMkumbi4 TYR1_r01	0.90	0.96	23.96	69.70	0.12	0.01	0.87	0.69	0.85	0.01	0.03	0.09	4.72	103
TzMkumbi4 TYR1_r02	1.22	0.93	23.91	69.45	0.13	0.01	0.85	0.68	0.86	0.01	0.03	0.09	4.74	103
Average	1.06	0.97	23.92	69.56	0.13	0.01	0.86	0.68	0.85	0.01	0.03	0.09	4.73	103
TzMkumbi4 TYR2	0.96	0.90	24.39	69.20	0.12	0.01	0.87	0.56	0.87	0.02	0.03	0.10	4.88	103
TzMkumbi4 TYR2_r01	1.12	0.95	24.39	69.06	0.12	0.01	0.87	0.55	0.87	0.02	0.03	0.10	4.84	103
TzMkumbi4 TYR2_r02	0.95	0.98	24.38	69.15	0.12	0.01	0.84	0.55	0.89	0.01	0.03	0.10	4.88	103
Average	1.01	0.94	24.39	69.14	0.12	0.01	0.86	0.55	0.88	0.02	0.03	0.10	4.87	103
TzMkumbi4 TYR3	1.08	0.98	24.73	68.81	0.09	0.01	0.84	0.57	0.87	0.02	0.03	0.09	4.79	103
TzMkumbi4 TYR3_r01	0.69	0.96	24.74	69.11	0.12	0.01	0.86	0.58	0.87	0.01	0.03	0.09	4.84	103
Average	0.89	0.97	24.74	68.96	0.10	0.01	0.85	0.58	0.87	0.02	0.03	0.09	4.82	103
TzMkumbi5B FW1	0.59	1.39	28.33	65.10	0.13	0.01	0.81	0.90	0.83	0.01	0.03	0.10	4.69	103
TzMkumbi5B FW1_r01	0.83	1.30	28.35	64.93	0.14	0.01	0.81	0.91	0.83	0.01	0.03	0.10	4.67	103
Average	0.71	1.35	28.34	65.02	0.13	0.01	0.81	0.90	0.83	0.01	0.03	0.10	4.68	103
TzMkumbi5B FW2	0.58	1.41	27.43	65.34	0.13	0.01	0.85	1.34	0.85	0.01	0.03	0.10	4.83	103
TzMkumbi5B FW2_r01	0.84	1.39	27.37	65.19	0.13	0.01	0.83	1.36	0.86	0.01	0.03	0.10	4.80	103
Average	0.71	1.40	27.40	65.27	0.13	0.01	0.84	1.35	0.85	0.01	0.03	0.10	4.82	103
TzMkumbi5B FW3	1.14	1.35	28.80	63.75	0.12	0.02	0.92	1.22	0.81	0.01	0.02	0.10	4.63	103
TzMkumbi5B FW3_r01	0.76	1.44	28.83	63.91	0.12	0.03	0.95	1.23	0.83	0.01	0.02	0.10	4.67	103
Average	0.95	1.40	28.82	63.83	0.12	0.03	0.94	1.23	0.82	0.01	0.02	0.10	4.65	103
TzMkumbi5B TB1	0.86	0.99	25.20	68.65	0.10	0.01	0.84	0.56	0.85	0.02	0.03	0.08	4.73	103
TzMkumbi5B TB1_r01	1.28	1.02	25.12	68.35	0.10	0.01	0.84	0.55	0.83	0.02	0.03	0.07	4.68	103
TzMkumbi5B TB1_r02	1.17	1.00	25.26	68.32	0.10	0.01	0.84	0.54	0.84	0.02	0.03	0.07	4.70	103
Average	1.10	1.01	25.19	68.44	0.10	0.01	0.84	0.55	0.84	0.02	0.03	0.08	4.70	103
TzMkumbi5B TB2	0.27	0.85	27.66	69.58	0.06	0.01	0.57	0.28	0.54	0.00	0.02	0.05	3.06	103
TzMkumbi5B TB2_r01	0.33	0.84	27.66	69.51	0.06	0.01	0.55	0.28	0.54	0.00	0.02	0.05	3.08	103

TzMkumbi5B TB2_r02	0.38	0.85	27.62	69.50	0.07	0.01	0.55	0.28	0.54	0.00	0.02	0.05	3.07	103
Average	0.33	0.85	27.65	69.53	0.06	0.01	0.56	0.28	0.54	0.00	0.02	0.05	3.07	103
TzMkumbi5B TB3	1.01	0.90	21.38	73.32	0.12	0.01	0.94	0.24	0.73	0.01	0.03	0.08	4.13	103
TzMkumbi5B TB3_r01	1.14	0.88	21.50	73.10	0.12	0.01	0.93	0.23	0.73	0.01	0.03	0.09	4.14	103
TzMkumbi5B TB3_r02	0.65	0.86	21.62	73.45	0.12	0.01	0.93	0.23	0.74	0.01	0.03	0.09	4.18	103
Average	0.93	0.88	21.50	73.29	0.12	0.01	0.93	0.24	0.73	0.01	0.03	0.09	4.15	103
TzMkumbi5B TYR1	0.54	1.14	28.22	66.29	0.09	0.02	1.17	0.15	0.77	0.01	0.02	0.06	4.45	103
TzMkumbi5B TYR1_r01	0.83	1.03	28.30	66.06	0.09	0.03	1.14	0.15	0.78	0.01	0.02	0.06	4.43	103
Average	0.69	1.09	28.26	66.18	0.09	0.02	1.16	0.15	0.78	0.01	0.02	0.06	4.44	103
TzMkumbi5B TYR2	0.82	1.13	27.64	66.77	0.07	0.02	1.10	0.13	0.76	0.01	0.02	0.06	4.39	103
TzMkumbi5B TYR2_r01	0.48	1.11	27.78	66.94	0.10	0.03	1.11	0.13	0.75	0.01	0.02	0.06	4.40	103
Average	0.65	1.12	27.71	66.86	0.09	0.03	1.11	0.13	0.75	0.01	0.02	0.06	4.39	103
TzMkumbi5B TYR3	0.90	0.99	26.05	68.39	0.05	0.02	1.11	0.11	0.74	0.01	0.02	0.06	4.46	103
TzMkumbi5B TYR3_r01	0.58	0.99	26.00	68.69	0.09	0.03	1.12	0.11	0.74	0.01	0.02	0.07	4.48	103
Average	0.74	0.99	26.03	68.54	0.07	0.02	1.11	0.11	0.74	0.01	0.02	0.07	4.47	103

Appendix 5.11: Full results of the (P) XRF-EDS trace element concentrations of the technical ceramics from Mkumbi smelting 4 and refining 5B sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and TBs=test briquettes

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	Ta2O5	WO3	PbO	Th
TzMkumbi4 FW1	72	43	57	61	15	57	49	33	242	20	135	32	49	7	10	12	17	18
TzMkumbi4 FW1_r01	75	39	58	60	15	58	50	34	244	20	139	31	49	11	6	8	17	17
Average	73	41	57	61	15	58	49	33	243	20	137	32	49	9	8	10	17	17
TzMkumbi4 FW2	66	39	50	56	14	50	48	31	232	16	124	31	47	8	9	44	16	18
TzMkumbi4 FW2_r01	64	36	48	55	13	51	49	30	226	15	124	32	51	11	8	37	16	17
Average	65	37	49	56	13	51	48	31	229	16	124	31	49	9	8	40	16	18
TzMkumbi4 FW3	77	43	66	63	15	51	56	33	241	19	133	30	48	9	7	68	17	18
TzMkumbi4 FW3_r01	73	43	59	62	14	51	57	33	246	18	135	31	50	11	10	68	17	20
Average	75	43	63	62	14	51	56	33	243	18	134	31	49	10	8	68	17	19
TzMkumbi4 TB1	75	28	65	50	13	45	33	30	271	18	105	30	51	12	11	102	92	21
TzMkumbi4 TB1_r01	94	31	70	52	14	44	34	31	261	16	102	33	54	11	7	108	90	19
Average	84	29	68	51	14	44	33	31	266	17	103	32	53	11	9	105	91	20
TzMkumbi4 TB2	86	23	45	45	10	39	25	30	298	14	90	30	50	13	9	143	143	19
TzMkumbi4 TB2_r01	88	23	46	48	12	39	25	29	301	16	93	31	51	12	6	144	145	19
Average	87	23	45	47	11	39	25	30	299	15	91	31	51	12	8	143	144	19
TzMkumbi4 TB3	98	35	69	60	15	48	25	33	235	18	95	33	53	8	8	147	22	18
TzMkumbi4 TB3_r01	120	32	71	54	14	47	25	34	250	17	98	32	53	9	10	143	21	19
Average	109	34	70	57	14	47	25	33	242	17	96	33	53	9	9	145	22	18
TzMkumbi4 TYR1	101	29	42	63	14	45	45	31	214	18	127	30	44	12	10	113	16	18
TzMkumbi4 TYR1_r01	93	32	47	65	14	45	45	31	206	16	123	30	46	8	7	111	16	18
TzMkumbi4 TYR1_r02	75	35	49	63	15	45	45	31	211	17	123	31	45	8	6	118	17	18
Average	90	32	46	64	14	45	45	31	210	17	124	30	45	9	8	114	16	18

TzMkumbi4 TYR2	68	34	52	71	14	46	42	32	218	21	140	30	48	11	9	95	17	18
TzMkumbi4 TYR2_r01	84	31	53	69	15	44	41	32	219	17	139	30	46	10	6	101	16	19
TzMkumbi4 TYR2_r02	58	38	53	71	14	45	41	32	214	17	145	32	50	10	9	98	17	19
Average	70	34	52	70	14	45	41	32	217	18	141	31	48	10	8	98	17	19
TzMkumbi4 TYR3	58	38	47	65	14	46	40	31	215	19	129	31	51	8	9	79	15	18
TzMkumbi4 TYR3_r01	53	40	47	63	14	45	40	32	217	17	127	30	49	10	7	80	15	18
Average	55	39	47	64	14	46	40	32	216	18	128	30	50	9	8	79	15	18
TzMkumbi5B FW1	67	33	64	56	14	44	49	30	207	17	127	30	47	9	7	85	18	16
TzMkumbi5B FW1_r01	70	34	60	54	12	43	49	30	205	14	126	29	45	9	14	73	19	17
Average	68	33	62	55	13	43	49	30	206	16	126	30	46	9	10	79	19	17
TzMkumbi5B FW2	82	36	57	58	15	46	56	32	223	18	137	32	50	9	5	66	25	17
TzMkumbi5B FW2_r01	78	29	56	57	13	46	56	32	222	18	139	31	48	10	10	57	25	18
Average	80	32	56	58	14	46	56	32	222	18	138	32	49	9	8	62	25	17
TzMkumbi5B FW3	103	34	51	57	14	47	61	32	228	15	135	26	44	8	9	33	15	18
TzMkumbi5B FW3_r01	77	33	49	58	13	47	62	32	231	20	138	28	44	11	11	30	15	18
Average	90	34	50	57	14	47	61	32	230	17	136	27	44	9	10	31	15	18
TzMkumbi5B TB1	80	31	81	49	13	42	35	30	231	15	100	30	48	9	9	63	27	19
TzMkumbi5B TB1_r01	96	27	81	50	11	42	34	30	234	17	100	30	48	8	14	63	27	19
TzMkumbi5B TB1_r02	86	33	82	54	13	43	34	30	230	19	97	29	51	10	12	66	27	20
Average	87	30	81	51	12	43	34	30	232	17	99	30	49	9	12	64	27	19
TzMkumbi5B TB2	25	22	41	32	7	30	26	21	200	12	92	22	33	7	6	39	33	13
TzMkumbi5B TB2_r01	33	22	42	33	8	30	25	21	201	14	91	23	34	6	7	38	33	12
TzMkumbi5B TB2_r02	46	16	43	31	8	30	26	21	194	12	96	25	37	6	5	33	33	13
Average	35	20	42	32	8	30	25	21	198	13	93	23	35	6	6	37	33	12
TzMkumbi5B TB3	80	25	55	49	11	41	26	30	227	14	104	32	49	7	9	99	22	18
TzMkumbi5B TB3_r01	72	28	56	52	11	42	26	31	226	16	103	28	46	9	8	87	21	19
TzMkumbi5B TB3_r02	77	24	52	51	10	42	26	31	233	14	104	31	51	10	10	89	23	18
Average	76	26	55	51	11	42	26	31	229	14	103	30	49	9	9	92	22	18
TzMkumbi5B TYR1	78	23	44	43	13	47	26	22	219	14	89	19	43	7	10	40	14	17

TzMkumbi5B TYR1_r01	67	26	43	43	13	46	25	21	221	16	88	19	47	9	8	45	15	17
Average	72	25	44	43	13	47	26	21	220	15	89	19	45	8	9	42	14	17
TzMkumbi5B TYR2	36	29	44	45	13	45	25	23	218	15	94	19	40	9	6	59	15	18
TzMkumbi5B TYR2_r01	41	30	46	45	13	44	25	23	221	16	94	20	45	9	5.7	63	15	18
Average	39	29	45	45	13	44	25	23	219	15	94	20	42	9	6	61	15	18
TzMkumbi5B TYR3	46	31	37	43	12	47	25	21	222	15	91	17	43	11	9	68	18	19
TzMkumbi5B TYR3_r01	63	22	38	44	13	46	26	23	224	14	95	21	47	10	9	57	18	20
Average	55	26	37	43	13	46	26	22	223	15	93	19	45	10	9	62	18	19

Appendix 5.12: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Mkumbi, Kamafupa, and Tupa sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Total
Slags from Mkumbi 6 and 9											
1	6SE1	0.4	12.7	40.6	0.4	1.5	1.1	0.9	1.4	41.5	100
2	6SE2	0.2	12.7	46.4	0.6	2.1	1.5	0.6	0.8	35.0	100
3	9RF1	0.3	11.7	35.2	0.2	1.7	0.7	0.7	1.9	48.1	100
4	9RF2	0.1	11.0	35.9	0.3	1.2	0.8	0.7	1.5	48.3	100
5	9RF3	0.2	9.5	30.3	0.3	1.3	0.6	0.7	1.3	56.4	101
Slags from Kamafupa11 and 9											
6	11SE1	0.2	9.7	26.6	0.4	1.6	1.5	0.4	0.2	59.9	101
7	11SE2	0.18	9.99	26.08	0.52	1.23	0.81	0.47	0.34	60.52	100
8	9RF1	0.2	13.2	33.0	0.3	1.3	0.6	0.6	0.9	50.3	100
9	9RF2	0.2	13.5	37.1	0.3	1.2	0.6	0.5	0.9	46.7	101
10	9RF3	0.3	9.4	27.4	0.4	1.1	1.4	0.4	0.2	59.2	100
Slags from Tupa 33, 34, and 8											
11	33SE1	0.1	7.8	40.8	0.2	0.9	0.7	0.5	0.0	49.3	100
12	34SE2	0.2	8.4	39.2	0.4	0.8	1.0	0.4	0.0	50.2	101
13	8RF1	0.1	9.3	35.4	0.2	0.6	0.8	0.6	0.1	53.4	100
14	8CKRF2	0.2	10.6	30.3	0.3	1.0	1.2	0.5	0.6	55.3	100
15	8RF3	0.2	8.7	28.0	0.4	0.7	0.7	0.4	0.6	60.1	100

Appendix 5.13: Full results of the SEM-EDS bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Kamafupa, Mkumbi, and Tupa sites. Note the results are normalised to 100 wt%, and the bulk areas were measured at *x*50

Sample	Area	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	MnO	FeO	BaO	Total
TzKamafupa9 RF1	Area 1	0.3	0.2	12.5	33.4	0.2	0.1	1.3	0.7	0.6	0.8	49.7	0.2	100.1
	Area 2	0.0	0.2	13.4	32.9	0.4	0.0	1.4	0.7	0.6	0.9	51.3	0.3	101.8
	Area 3	0.1	0.2	13.3	32.8	0.3	0.3	1.4	0.7	0.7	0.8	50.6	0.3	101.6
	Average	0.1	0.2	13.0	33.1	0.3	0.1	1.4	0.7	0.6	0.8	50.5	0.3	101.1
TzKamafupa9 RF2	Area 1	0.2	0.2	13.9	36.6	0.6	0.0	1.3	0.7	0.5	0.9	46.2	0.0	101.4
	Area 2	0.1	0.1	14.2	37.0	0.2	0.0	1.2	0.7	0.6	0.9	46.0	0.2	101.2
	Area 3	0.1	0.2	13.0	37.0	0.3	0.1	1.2	0.6	0.4	0.9	47.0	0.0	100.8
	Average	0.1	0.2	13.7	36.9	0.4	0.0	1.2	0.7	0.5	0.9	46.4	0.0	101.1
TzKamafupa9 RF3	Area 1	0.1	0.4	9.2	27.8	0.4	0.0	1.0	1.3	0.4	0.3	59.8	0.1	100.3
	Area 2	0.2	0.2	9.4	27.0	0.4	0.1	1.0	1.4	0.4	0.3	60.0	0.0	100.6

	Area 3	0.1	0.4	8.7	27.5	0.5	0.3	1.0	1.3	0.3	0.4	59.5	0.2	100.4
	Average	0.1	0.4	9.1	27.4	0.4	0.2	1.0	1.3	0.4	0.3	59.8	0.1	100.4
TzKamafupa11 SE1	Area 1	0.0	0.3	11.3	26.0	0.5	0.2	1.8	1.3	0.4	0.1	58.5	0.1	100.7
	Area 2	0.0	0.3	12.3	26.0	0.6	0.0	1.8	1.4	0.4	0.3	58.9	0.1	102.1
	Area 3	0.1	0.4	10.1	26.8	0.3	0.3	1.6	1.4	0.3	0.3	59.4	0.0	101.2
	Average	0.0	0.4	11.2	26.3	0.5	0.1	1.7	1.4	0.4	0.2	58.9	0.1	101.3
TzKamafupa11 SE2	Area 1	0.2	0.4	9.0	43.9	0.4	0.0	3.5	0.8	0.4	0.3	42.1	0.0	100.5
	Area 2	0.1	1.9	9.2	28.2	1.2	0.0	2.6	2.3	0.3	0.2	55.3	0.1	101.4
	Area 3	0.2	0.2	6.4	51.8	0.3	0.1	3.2	0.6	0.4	0.2	36.4	0.0	99.7
	Average	0.2	0.8	8.2	41.3	0.6	0.0	3.1	1.2	0.3	0.2	44.6	0.0	100.5
TzMkumbi9 RF1	Area 1	0.0	0.3	12.2	34.0	0.1	0.1	1.7	0.7	0.7	1.8	49.1	0.3	101.2
	Area 2	0.1	0.2	10.8	34.1	0.1	0.0	1.7	0.8	0.8	1.7	49.6	0.5	100.1
	Area 3	0.1	0.4	10.2	34.2	0.3	0.1	1.8	0.7	0.5	1.6	49.2	0.3	99.7
	Average	0.1	0.3	11.1	34.1	0.2	0.1	1.7	0.7	0.7	1.7	49.3	0.4	100.3
TzMkumbi9 RF2	Area 1	0.1	0.2	12.1	35.6	0.1	0.1	1.2	0.8	0.6	1.4	48.3	0.5	100.8
	Area 2	0.2	0.2	12.6	35.2	0.2	0.0	1.1	0.7	0.5	1.3	48.4	0.4	101.1
	Area 3	0.1	0.2	11.1	34.5	0.2	0.2	1.2	0.7	0.6	1.4	48.5	0.6	99.6
	Average	0.1	0.2	11.9	35.1	0.2	0.1	1.2	0.8	0.6	1.4	48.4	0.5	100.5
TzMkumbi9 RF3	Area 1	0.2	0.2	9.2	29.9	0.4	0.3	1.2	0.6	0.6	1.5	56.0	0.3	100.5
	Area 2	0.0	0.3	9.2	30.9	0.2	0.2	1.2	0.8	0.6	1.4	55.4	0.1	100.4
	Area 3	0.5	0.1	8.7	30.1	0.2	0.1	1.2	0.7	0.4	1.4	56.1	0.3	100.0
	Average	0.2	0.2	9.0	30.3	0.3	0.2	1.2	0.7	0.5	1.4	55.8	0.2	100.3
TzMkumbi6 SE1	Area 1	0.3	0.2	12.2	40.7	0.5	-0.1	1.4	1.2	0.7	1.5	41.7	0.3	100.3
	Area 2	0.2	0.1	13.6	40.4	0.2	0.1	1.4	1.1	0.8	1.5	41.8	0.1	101.4
	Area 3	0.1	0.2	10.7	40.5	0.4	0.1	1.6	1.2	0.6	1.4	42.3	0.3	99.5
	Average	0.2	0.2	12.2	40.5	0.3	0.0	1.5	1.1	0.7	1.4	41.9	0.2	100.4
TzMkumbi6 SE2	Area 1	0.0	0.3	12.5	45.6	0.5	0.4	2.0	1.5	0.6	0.9	37.0	0.2	101.6
	Area 2	0.2	0.1	11.9	45.5	0.6	0.3	2.1	1.4	0.6	0.9	36.8	0.1	100.4
	Area 3	0.2	0.1	13.9	46.5	0.6	0.0	2.1	1.6	0.6	0.8	35.5	0.4	102.0
	Average	0.1	0.2	12.8	45.9	0.6	0.2	2.0	1.5	0.6	0.8	36.4	0.2	101.3
TzTupa8 RF1	Area 1	0.1	0.2	9.9	39.2	0.2	0.3	0.5	1.1	0.7	0.0	48.5	-0.1	100.7
	Area 2	0.2	0.2	9.2	35.7	0.3	-0.2	0.7	1.0	0.5	0.0	53.7	0.0	100.9
	Area 3	0.1	0.2	10.5	36.7	0.4	0.1	0.6	0.8	0.5	0.0	51.6	-0.1	101.6
	Average	0.1	0.2	9.9	37.2	0.3	0.0	0.6	1.0	0.6	0.0	51.3	-0.1	101.1
TzTupa8 RF2	Area 1	0.1	0.2	10.8	32.0	0.3	0.1	0.9	1.2	0.4	0.5	53.2	0.1	100.3
	Area 2	0.1	0.3	11.9	36.4	0.2	0.1	0.8	1.3	0.8	0.6	47.0	0.0	99.7
	Area 3	0.2	0.1	10.4	31.1	0.4	0.0	1.0	1.3	0.2	0.4	54.8	0.4	100.2
	Average	0.2	0.2	11.0	33.1	0.3	0.1	0.9	1.3	0.5	0.5	51.7	0.2	100.1
TzTupa8 RF3	Area 1	0.2	0.0	9.2	26.2	0.3	0.3	0.7	0.7	0.3	0.7	62.0	0.0	100.8
	Area 2	-0.1	0.0	8.8	27.9	0.2	0.1	0.8	0.6	0.2	0.7	60.1	0.3	99.8
	Area 3	0.0	0.2	10.1	27.0	0.5	0.1	0.7	0.8	0.4	0.7	60.8	0.1	101.5
	Average	0.0	0.1	9.3	27.0	0.3	0.2	0.7	0.7	0.3	0.7	61.0	0.1	100.7
TzTupa33 SE1	Area 1	0.1	0.0	7.1	38.2	0.2	0.0	0.8	0.4	0.6	0.1	53.0	-0.4	100.3
	Area 2	0.1	0.1	7.6	39.5	0.2	-0.1	0.9	0.5	0.6	0.1	51.5	0.0	100.6

	Area 3	0.1	0.1	7.9	39.7	0.2	0.2	0.9	0.7	0.5	0.0	50.3	0.0	100.6
	Average	0.1	0.1	7.5	39.1	0.2	0.0	0.8	0.5	0.6	0.1	51.6	-0.1	100.5
TzTupa34 SE1	Area 1	0.1	0.2	4.3	49.8	0.3	-0.1	0.6	0.8	0.1	0.0	42.7	0.4	99.0
	Area 2	0.0	0.1	8.0	35.1	0.5	0.1	0.7	0.9	0.4	0.2	55.0	-0.1	101.2
	Area 3	0.1	0.3	6.8	35.4	0.0	0.1	0.7	0.8	0.4	0.0	55.8	0.1	100.5
	Average	0.0	0.2	6.4	40.1	0.2	0.0	0.7	0.8	0.3	0.1	51.1	0.1	100.2

Appendix 5.14: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Kamafupa, Mkumbi, and Tupa sites. Note the results are not normalised to 100 wt%

Sample	Co3O4	NiO	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Ba	Ce	Hf	Ta2O5	WO3	Th	U
TzKamafupa11 FSE2	166	11	32	20	69	25	70	15	126	71	13	14	18	13	10
TzKamafupa11 FSE_r01	150	11	27	16	65	25	69	13	137	44	14	15	17	13	9
TzKamafupa11 FSE_r02	254	11	33	17	68	26	82	15	140	68	13	21	16	13	11
Average	190	11	31	17	68	25	73	14	134	61	13	17	17	13	10
TzKamafupa11 TSE1	150	12	42	29	94	23	57	12	146	71	14	18	19	13	10
TzKamafupa11 TSE_r01	150	11	35	27	92	22	60	8	148	67	13	14	19	13	11
TzKamafupa11 TSE_r02	223	12	21	28	94	23	60	14	141	65	14	17	19	13	6
Average	174	12	33	28	93	23	59	11	145	68	14	16	19	13	9
TzKamafupa9 RF1	145	8	19	4	56	23	93	20	402	62	11	10	15	10	8
TzKamafupa9 RF1_r01	207	9	21	13	58	22	96	14	409	62	11	30	15	10	11
TzKamafupa9 RF1_r02	130	8	29	4	57	23	81	11	417	70	12	12	15	10	15
Average	161	8	23	7	57	22	90	15	409	64	11	17	15	10	11
TzKamafupa9 RF2	166	8	29	9	52	18	159	30	403	119	11	11	176	9	9
TzKamafupa9 RF2_r01	120	8	18	4	50	18	162	26	392	118	10	11	181	9	10
TzKamafupa9 RF2_r02	203	8	20	4	51	18	153	32	402	115	11	11	158	9	10
Average	163	8	22	6	51	18	158	29	399	117	11	11	172	9	10
TzKamafupa9 RF3	158	11	32	9	81	17	85	14	221	27	15	16	77	13	19
TzKamafupa9 RF3_r01	364	12	46	11	84	18	91	10	221	26	15	16	22	13	10
TzKamafupa9 RF3_r02	150	12	41	15	83	18	82	12	224	30	15	21	36	13	9
Average	224	12	40	12	83	18	86	12	222	28	15	18	45	13	13
TzMkumbi6 SE1	110	8	15	20	73	19	94	12	706	70	9	19	205	8	10
TzMkumbi6 SE1_r01	110	8	25	24	75	20	79	13	700	68	10	10	198	8	6
TzMkumbi6 SE1_r02	158	8	9	19	74	18	95	18	707	77	10	10	215	8	9

Average	126	8	16	21	74	19	89	14	704	72	10	13	206	8	8
TzMkumbi6 SE2	105	6	24	24	71	19	103	13	621	65	8	8	162	5	9
TzMkumbi6 SE2_r01	92	6	29	19	71	19	102	12	619	63	8	9	163	5	8
TzMkumbi6 SE2_r02	176	6	27	20	71	19	96	9	618	70	8	9	172	5	9
Average	124	6	27	21	71	19	100	11	619	66	8	9	166	5	8
TzMkumbi9 RF1	130	9	22	7	69	22	87	17	871	73	11	11	130	10	9
TzMkumbi9 RF1_r01	130	8	30	4	71	22	83	18	871	72	11	11	149	10	10
TzMkumbi9 RF1_r02	130	8	19	4	68	21	82	13	863	64	11	11	147	10	9
Average	130	8	24	5	69	22	84	16	868	70	11	11	142	10	9
TzMkumbi9 RF2	151	8	21	4	60	20	115	18	794	101	10	10	17	10	9
TzMkumbi9 RF2_r01	130	9	13	3	63	19	109	22	816	98	10	10	16	10	10
TzMkumbi9 RF2_r02	150	8	11	4	63	18	108	18	801	94	11	19	17	10	9
Average	144	8	15	4	62	19	110	19	804	97	10	13	17	10	9
TzMkumbi9 RF3	140	10	29	12	59	22	89	15	730	68	11	15	16	12	11
TzMkumbi9 RF3_r01	140	10	26	4	60	21	94	20	736	73	13	11	17	12	12
TzMkumbi9 RF3_r02	118	10	20	10	59	20	82	16	731	79	12	13	18	12	10
Average	133	10	25	9	59	21	88	17	733	73	12	13	17	12	11
TzTupa33 SE1	130	9	12	13	61	16	108	7	90	16	11	26	18	11	20
TzTupa33 SE1_r01	130	9	20	11	65	17	103	15	91	16	11	8	18	11	10
TzTupa33 SE1_r02	130	9	16	11	66	16	109	6	94	21	11	21	18	10	14
Average	130	9	16	12	64	16	107	9	92	17	11	18	18	11	15
TzTupa34 SE1	130	10	12	20	50	17	85	20	49	21	13	37	22	11	10
TzTupa34 SE1_r01	130	9	9	20	51	16	85	12	51	23	12	14	131	11	16
TzTupa34 SE1_r02	130	10	26	19	53	16	79	17	47	25	13	13	96	11	9
Average	130	10	16	19	51	16	83	16	49	23	13	21	83	11	12
TzTupa8 CKRF2	130	9	14	16	83	19	93	18	272	33	11	11	16	11	7
TzTupa8 CKRF2_r01	334	9	11	18	84	18	88	14	283	33	11	10	16	11	14
TzTupa8 CKRF2_r02	337	9	20	17	83	17	91	25	285	27	11	12	16	11	9
Average	267	9	15	17	83	18	91	19	280	31	11	11	16	11	10
TzTupa8 RF1	130	9	20	7	65	15	105	20	72	16	10	12	93	11	10

TzTupa8 RF1_r01	130	9	15	4	65	16	96	16	75	19	11	26	19	11	8
TzTupa8 RF1_r02	130	9	29	4	63	15	102	21	73	27	12	12	19	11	10
Average	130	9	21	5	64	15	101	19	73	21	11	17	44	11	9
TzTupa8 RF3	150	9	17	4	58	16	80	16	442	34	12	12	129	14	8
TzTupa8 RF3_r01	258	11	25	4	59	17	96	17	454	33	13	13	21	14	11
TzTupa8 RF3_r02	150	10	20	4	56	17	86	9	452	37	12	13	20	14	13
Average	186	10	21	4	57	17	87	14	449	35	12	13	57	14	11

Appendix 5.15: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Mkumbi sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

S/No.	Sample/ Oxides	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Total
Set I: Mkumbi SE3 and RF2											
1	3SE3	0.2	11.6	47.1	0.4	1.4	1.0	0.8	1.4	36.0	100
2	3SE4	0.1	12.5	44.1	0.4	1.1	1.2	0.7	0.6	39.3	100
3	3SE5	0.9	10.8	46.2	1.1	1.9	8.7	0.8	3.2	26.4	100
4	3SE6	0.2	11.6	47.2	0.4	1.4	0.9	0.8	1.4	36.1	100
5	3SE7	0.2	11.3	48.6	0.4	1.6	1.1	0.8	1.4	34.5	100
6	2RF4	0.2	8.9	33.0	0.3	0.8	1.0	0.6	0.2	55.0	100
7	2RF5	0.1	11.4	32.9	0.4	1.5	0.7	0.7	1.2	51.2	100
8	2RF6	0.3	12.8	32.4	0.2	1.4	0.6	0.8	1.7	50.0	100
9	2RF7	0.3	12.8	33.5	0.2	1.4	1.0	0.8	1.5	48.7	100
10	2RF8	0.3	12.7	32.2	0.1	1.6	1.6	0.7	1.6	49.3	100
Set II: Mkumbi SE4 and RF5B											
11	4SE8	0.2	13.0	33.4	0.3	0.5	1.4	0.5	1.3	49.5	100
12	4SE9	0.2	13.4	35.7	0.4	0.6	1.7	0.5	1.2	46.2	100
13	4SE10	0.3	13.5	37.8	0.4	0.7	1.9	0.6	1.3	43.4	100
14	4SE11	0.2	12.4	39.3	0.3	1.0	1.6	0.8	2.5	41.8	100
15	4SE12	0.2	12.6	40.8	0.3	1.1	1.8	0.7	2.4	40.1	100
16	5BRF9	0.1	10.1	35.5	0.4	0.7	0.7	0.5	0.4	51.7	100
17	5BRF10	0.1	9.3	36.8	0.2	0.9	0.8	0.6	0.4	50.8	100
18	5BRF11	0.1	9.9	37.9	0.3	0.9	0.8	0.7	0.5	48.8	100
19	5BRF12	0.1	9.9	39.2	0.3	0.6	0.3	0.6	0.7	48.2	100
20	5BRF13	0.1	9.4	36.7	0.3	0.8	0.8	0.6	0.4	50.9	100

Appendix 5.16: Full results of the SEM-EDS bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Mkumbi sites. Note the results are normalised to 100 wt%, and the bulk areas were measured at *x*50

Sample	Area	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Total
Mkumbi3 SE3	Area 1	0.1	11.6	47.2	0.7	1.5	1.2	0.8	1.4	35.4	100
	Area 2	0.2	11.7	47.0	0.4	1.2	0.9	0.9	1.4	36.4	100
	Area 3	0.2	11.6	47.0	0.3	1.4	0.9	0.8	1.4	36.3	100
	Mean	0.2	11.6	47.1	0.4	1.4	1.0	0.8	1.4	36.0	100
Mkumbi3 SE4	Area 1	0.0	12.4	43.9	0.3	1.0	1.0	0.7	0.7	39.9	100
	Area 2	0.1	12.8	44.3	0.3	1.1	1.2	0.8	0.6	38.8	100

	Area 3	0.2	12.3	44.0	0.5	1.1	1.6	0.7	0.5	39.1	100
	Mean	0.1	12.5	44.1	0.4	1.1	1.2	0.7	0.6	39.3	100
Mkumbi3 SE5	Area 1	0.9	11.3	46.3	1.2	2.1	8.7	0.9	3.5	25.1	100
	Area 2	1.4	10.1	46.3	1.4	2.0	11.0	0.7	3.0	24.0	100
	Area 3	0.5	11.1	46.0	0.7	1.6	6.3	0.7	3.1	30.0	100
	Mean	0.9	10.8	46.2	1.1	1.9	8.7	0.8	3.2	26.4	100
Mkumbi3 SE6	Area 1	0.3	11.1	47.5	0.4	1.6	1.2	0.9	1.3	35.7	100
	Area 2	0.2	11.5	47.9	0.4	1.6	1.0	0.7	1.4	35.2	100
	Area 3	0.0	12.1	46.3	0.3	1.1	0.5	0.9	1.5	37.4	100
	Mean	0.2	11.6	47.2	0.4	1.4	0.9	0.8	1.4	36.1	100
Mkumbi3 SE7	Area 1	0.2	11.6	48.7	0.4	1.6	1.2	0.8	1.4	34.2	100
	Area 2	0.3	11.3	48.7	0.5	1.7	1.2	0.7	1.4	34.3	100
	Area 3	0.2	11.2	48.5	0.2	1.4	0.9	0.9	1.4	35.2	100
	Mean	0.2	11.3	48.6	0.4	1.6	1.1	0.8	1.4	34.5	100
Mkumbi2 RF4	Area 1	0.1	9.5	33.0	0.4	0.9	1.0	0.6	0.3	54.4	100
	Area 2	0.2	8.3	32.6	0.3	0.7	0.9	0.5	0.2	56.3	100
	Area 3	0.2	8.9	33.3	0.1	0.9	1.1	0.7	0.2	54.4	100
	Mean	0.2	8.9	33.0	0.3	0.8	1.0	0.6	0.2	55.0	100
Mkumbi2 RF5	Area 1	0.1	11.4	32.7	0.3	1.5	0.8	0.7	1.1	51.4	100
	Area 2	0.1	11.3	33.3	0.5	1.5	0.7	0.6	1.3	50.8	100
	Area 3	0.2	11.4	32.8	0.3	1.4	0.6	0.7	1.0	51.5	100
	Mean	0.1	11.4	32.9	0.4	1.5	0.7	0.7	1.2	51.2	100
Mkumbi2 RF6	Area 1	0.3	12.3	32.7	0.1	1.3	0.5	0.8	1.7	50.2	100
	Area 2	0.2	12.8	32.1	0.2	1.5	0.6	0.8	1.6	50.2	100
	Area 3	0.3	13.2	32.2	0.3	1.3	0.6	0.8	1.7	49.5	100
	Mean	0.3	12.8	32.4	0.2	1.4	0.6	0.8	1.7	50.0	100
Mkumbi2 RF7	Area 1	0.2	12.6	33.1	0.1	1.4	0.9	0.7	1.4	49.6	100
	Area 2	0.3	12.7	33.2	0.2	1.3	0.9	0.8	1.5	49.0	100
	Area 3	0.3	13.0	34.2	0.3	1.5	1.0	0.8	1.4	47.5	100
	Mean	0.3	12.8	33.5	0.2	1.4	1.0	0.8	1.5	48.7	100
Mkumbi2 RF8	Area 1	0.4	11.8	32.1	0.2	1.5	1.7	0.6	1.6	49.9	100
	Area 2	0.3	13.1	32.2	0.0	1.6	1.5	0.7	1.5	49.0	100
	Area 3	0.3	13.1	32.1	0.0	1.6	1.7	0.7	1.7	48.9	100
	Mean	0.3	12.7	32.2	0.1	1.6	1.6	0.7	1.6	49.3	100
Mkumbi4 SE8	Area 1	0.3	13.3	34.5	0.3	0.6	1.5	0.4	1.1	48.1	100
	Area 2	0.0	12.6	31.7	0.3	0.5	1.2	0.5	1.4	51.8	100
	Area 3	0.2	12.9	34.1	0.3	0.5	1.4	0.6	1.3	48.6	100
	Mean	0.2	13.0	33.4	0.3	0.5	1.4	0.5	1.3	49.5	100
Mkumbi4 SE9	Area 1	0.1	13.8	35.2	0.3	0.7	1.6	0.6	1.1	46.6	100
	Area 2	0.4	13.2	36.3	0.3	0.6	2.0	0.5	1.2	45.4	100
	Area 3	0.2	13.2	35.5	0.4	0.6	1.6	0.5	1.3	46.7	100
	Mean	0.2	13.4	35.7	0.4	0.6	1.7	0.5	1.2	46.2	100
Mkumbi4 SE10	Area 1	0.2	13.5	37.7	0.4	0.8	2.0	0.6	1.4	43.4	100
	Area 2	0.2	13.7	37.6	0.4	0.8	2.0	0.7	1.3	43.3	100

	Area 3	0.4	13.2	38.0	0.5	0.7	1.7	0.6	1.2	43.6	100
	Mean	0.3	13.5	37.8	0.4	0.7	1.9	0.6	1.3	43.4	100
Mkumbi4 SE11	Area 1	0.2	13.6	36.5	0.2	0.9	1.5	0.9	2.5	43.6	100
	Area 2	0.3	11.7	40.6	0.4	1.0	1.7	0.7	2.5	41.1	100
	Area 3	0.2	11.8	40.7	0.4	1.1	1.6	0.7	2.7	40.8	100
	Mean	0.2	12.4	39.3	0.3	1.0	1.6	0.8	2.5	41.8	100
Mkumbi4 SE12	Area 1	0.2	12.2	41.4	0.4	1.1	1.8	0.6	2.3	40.0	100
	Area 2	0.2	13.0	40.5	0.2	1.1	1.9	0.8	2.5	39.8	100
	Area 3	0.2	12.6	40.4	0.4	1.0	1.7	0.8	2.3	40.6	100
	Mean	0.2	12.6	40.8	0.3	1.1	1.8	0.7	2.4	40.1	100
Mkumbi5B RF9	Area 1	0.2	10.3	35.8	0.3	0.7	0.6	0.6	0.4	51.1	100
	Area 2	0.1	10.3	34.5	0.5	0.7	0.7	0.6	0.4	52.4	100
	Area 3	0.0	9.8	36.3	0.3	0.6	0.7	0.4	0.3	51.5	100
	Mean	0.1	10.1	35.5	0.4	0.7	0.7	0.5	0.4	51.7	100
Mkumbi5B RF10	Area 1	0.1	8.3	36.0	0.2	0.9	0.8	0.5	0.5	52.8	100
	Area 2	0.1	9.1	36.3	0.3	1.0	0.7	0.5	0.3	51.8	100
	Area 3	0.2	10.6	38.1	0.3	0.9	0.9	0.7	0.5	47.8	100
	Mean	0.1	9.3	36.8	0.2	0.9	0.8	0.6	0.4	50.8	100
Mkumbi5B RF11	Area 1	0.1	9.6	37.5	0.4	1.0	0.8	0.5	0.6	49.5	100
	Area 2	0.1	10.0	38.2	0.2	0.9	0.8	0.7	0.6	48.5	100
	Area 3	0.0	10.2	38.1	0.5	0.9	0.8	0.7	0.3	48.5	100
	Mean	0.1	9.9	37.9	0.3	0.9	0.8	0.7	0.5	48.8	100
Mkumbi5B RF12	Area 1	0.0	10.4	39.3	0.4	0.6	0.3	0.7	0.7	47.6	100
	Area 2	0.3	9.9	38.9	0.4	0.7	0.3	0.6	0.7	48.2	100
	Area 3	-0.1	9.3	39.5	0.1	0.5	0.4	0.6	0.7	48.9	100
	Mean	0.1	9.9	39.2	0.3	0.6	0.3	0.6	0.7	48.2	100
Mkumbi5B RF13	Area 1	0.0	9.0	36.9	0.3	0.8	0.8	0.6	0.4	51.2	100
	Area 2	0.1	9.5	36.7	0.4	0.7	0.8	0.5	0.5	50.8	100
	Area 3	0.1	9.7	36.6	0.4	0.8	0.7	0.6	0.4	50.6	100
	Mean	0.1	9.4	36.7	0.3	0.8	0.8	0.6	0.4	50.9	100

Appendix 5.17: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Mkumbi sites. Note the results are not normalised to 100 wt%

Sample	Co3O4	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Ba	Ce	Hf	Ta2O5	WO3	Th	U
TzMkumbi3 SE3_r01	100	19	27	90	18	174	17	802	112	8	8	12	6	9
TzMkumbi3 SE3_r02	100	20	32	91	19	177	17	812	116	9	9	31	7	9
Average	100	20	29	90	18	176	17	807	114	9	8	21	6	9
TzMkumbi3 SE4	182	18	19	95	15	129	18	386	82	10	10	13	8	8
TzMkumbi3 SE4_r01	110	20	21	92	16	125	19	392	73	10	9	14	8	9
TzMkumbi3 SE4_r02	252	13	21	94	16	122	16	388	83	10	20	13	8	8
Average	181	17	20	94	16	125	17	389	79	10	13	13	8	8
TzMkumbi3 SE5	87	19	11	431	28	156	31	1698	124	8	7	10	5	9
TzMkumbi3 SE5_r01	85	23	12	427	28	149	28	1675	131	7	7	15	4	9
TzMkumbi3 SE5_r02	85	16	11	434	28	161	35	1709	137	7	16	9	5	9
Average	86	19	11	431	28	155	31	1694	131	7	10	11	4	9
TzMkumbi3 SE6	100	19	20	82	19	183	12	792	104	9	8	55	6	12
TzMkumbi3 SE6_r01	99	20	21	78	17	170	18	790	101	8	6	56	6	9
TzMkumbi3 SE6_r02	99	18	17	81	18	178	15	792	99	9	8	13	6	11
Average	99	19	19	80	18	177	15	791	101	9	8	41	6	11
TzMkumbi3 SE7	99	18	20	92	18	169	14	803	101	8	13	12	6	17
TzMkumbi3 SE7_r01	98	17	17	92	18	174	13	813	110	8	8	11	6	14
TzMkumbi3 SE7_r02	99	18	22	91	18	171	14	802	108	9	8	11	6	9
Average	99	18	20	92	18	171	14	806	106	8	10	11	6	13
TzMkumbi2 RF4	130	34	3	77	19	93	19	118	30	13	13	14	11	8
TzMkumbi2 RF4_r01	130	43	6	74	19	102	13	114	35	13	12	14	12	21
TzMkumbi2 RF4_r02	140	33	7	72	20	98	18	117	29	13	13	13	11	9
Average	133	36	5	75	19	98	16	116	31	13	13	14	11	12
TzMkumbi2 RF5	130	19	12	71	22	78	14	567	72	11	18	15	11	10

TzMkumbi2 RF5_r01	130	23	12	74	22	88	17	558	50	12	13	15	11	11
TzMkumbi2 RF5_r02	130	33	11	74	22	76	11	570	73	12	12	15	11	10
Average	130	25	12	73	22	81	14	565	65	12	14	15	11	10
TzMkumbi2 RF6	130	29	12	65	17	89	13	694	65	11	12	14	10	14
TzMkumbi2 RF6_r01	130	26	13	62	17	82	19	683	63	12	12	14	10	10
TzMkumbi2 RF6_r02	130	24	16	65	19	89	12	686	47	11	21	15	10	11
Average	130	27	14	64	18	86	15	688	58	11	15	14	10	12
TzMkumbi2 RF7	120	31	12	78	19	80	12	563	71	11	9	16	10	10
TzMkumbi2 RF7_r01	120	30	10	77	19	79	7	555	71	12	12	17	10	9
TzMkumbi2 RF7_r02	130	12	12	76	19	79	14	549	52	11	21	16	10	10
Average	123	24	11	77	19	79	11	556	65	11	14	16	10	10
TzMkumbi2 RF8	120	24	14	123	22	73	13	630	67	11	10	15	10	11
TzMkumbi2 RF8_r01	130	21	9	122	19	69	20	611	80	11	21	15	10	10
TzMkumbi2 RF8_r02	120	16	10	125	20	72	19	625	77	10	9	15	10	10
Average	123	20	11	123	20	72	17	622	75	11	13	15	10	10
TzMkumbi4 SE8	130	15	9	73	22	165	30	628	121	11	12	14	10	12
TzMkumbi4 SE8_r01	104	27	17	72	23	158	38	650	124	12	14	14	11	8
TzMkumbi4 SE8_r02	130	20	14	76	22	162	30	635	117	11	20	12	10	15
Average	121	20	13	74	22	162	32	638	121	11	15	13	10	12
TzMkumbi4 SE9	97	23	9	105	21	163	32	651	105	12	29	16	9	13
TzMkumbi4 SE9_r01	286	21	10	109	21	158	30	634	106	11	12	60	9	9
TzMkumbi4 SE9_r02	120	16	9	108	21	161	28	623	106	11	25	16	9	8
Average	168	20	9	107	21	161	30	636	106	11	22	31	9	10
TzMkumbi4 SE10	120	8	9	90	21	175	28	652	118	10	12	13	9	8
TzMkumbi4 SE10_r01	120	14	15	92	22	166	30	661	120	10	14	14	9	16
TzMkumbi4 SE10_r02	158	28	9	93	21	182	28	655	108	10	10	15	9	10
Average	133	17	11	92	22	174	29	656	115	10	12	14	9	11
TzMkumbi4 SE11	110	24	17	112	20	122	24	1443	110	10	14	12	8	9
TzMkumbi4 SE11_r01	110	24	15	112	20	124	30	1431	110	10	10	13	8	10
TzMkumbi4 SE11_r02	110	29	20	113	19	126	31	1419	114	11	10	12	8	7
Average	110	26	17	112	20	124	28	1431	111	10	11	12	8	9

TzMkumbi4 SE12	110	22	16	111	19	133	33	1389	108	10	20	13	8	10
TzMkumbi4 SE12_r01	110	17	15	113	19	120	28	1395	108	9	25	13	8	10
TzMkumbi4 SE12_r02	110	24	19	113	19	126	22	1379	101	10	17	13	8	9
Average	110	21	16	112	19	126	28	1388	106	10	21	13	8	10
TzMkumbi5B RF9	130	31	9	46	14	102	14	194	54	12	13	15	11	10
TzMkumbi5B RF9_r01	130	36	12	49	16	92	15	192	40	11	13	14	11	10
TzMkumbi5B RF9_r02	438	29	14	45	15	90	15	185	37	11	22	14	10	9
Average	233	32	11	46	15	95	15	190	44	11	16	14	11	10
TzMkumbi5B RF10	110	45	8	64	15	90	14	297	66	10	11	11	8	10
TzMkumbi5B RF10_r01	298	43	3	66	15	103	10	300	51	11	12	12	8	7
TzMkumbi5B RF10_r02	110	29	3	64	15	93	6	306	55	10	26	11	8	8
Average	173	39	5	64	15	95	10	301	57	10	16	11	8	8
TzMkumbi5B RF11	130	28	4	60	16	102	15	274	50	11	12	16	10	9
TzMkumbi5B RF11_r01	130	34	13	63	16	104	11	268	44	11	12	16	10	11
TzMkumbi5B RF11_r02	130	27	7	61	16	107	11	273	64	12	15	50	10	9
Average	130	30	8	61	16	104	12	272	53	11	13	27	10	10
TzMkumbi5B RF12	120	33	7	29	16	117	17	202	57	12	12	13	10	9
TzMkumbi5B RF12_r01	120	26	8	29	16	114	11	198	39	11	21	15	10	14
TzMkumbi5B RF12_r02	120	31	13	31	15	119	10	204	45	11	20	15	10	11
Average	120	30	9	30	16	117	13	201	47	11	18	14	10	11
TzMkumbi5B RF13	130	37	4	66	15	108	15	278	54	12	12	17	11	9
TzMkumbi5B RF13_r01	130	25	11	66	16	109	19	272	66	12	12	16	11	11
TzMkumbi5B RF13_r02	130	33	11	68	17	109	8	276	40	13	14	16	11	10
Average	130	31	9	67	16	109	14	275	53	12	13	16	11	10

Appendix 5.18: Full results of the SEM-EDS chemical composition (in wt%) of fayalitic crystals in the smelting (SE) and refining (RF) slags from Mkumbi sites. Note the results are normalised to 100 wt%

Sample	Spectrum	MgO	Al2O3	SiO2	P2O5	CaO	TiO2	MnO	FeO	Total
Mkumbi3 SE3	Spectrum 1	0.7	0.0	30.8	0.0	0.0	0.0	2.1	66.5	100
	Spectrum 2	0.6	0.0	30.4	0.2	0.0	0.0	2.1	66.6	100
	Spectrum 3	0.6	0.0	30.3	0.2	0.1	-0.1	2.1	66.7	100
	Average	0.6	0.0	30.5	0.1	0.1	0.0	2.1	66.6	100
Mkumbi3 SE4	Spectrum 1	1.5	0.0	32.0	0.5	0.1	0.1	0.9	64.9	100
	Spectrum 2	0.6	0.1	32.2	0.0	0.1	0.0	1.0	65.9	100
	Spectrum 3	1.8	0.0	32.0	-0.1	0.2	0.1	1.0	65.1	100
	Average	1.3	0.0	32.1	0.1	0.1	0.1	1.0	65.3	100
Mkumbi3 SE5	Spectrum 1	3.5	0.1	31.4	0.3	0.5	0.1	6.2	57.9	100
	Spectrum 2	3.9	0.0	30.9	0.7	0.5	-0.1	6.4	57.7	100
	Spectrum 3	3.5	0.0	31.1	0.7	0.7	0.0	6.0	58.0	100
	Average	3.6	0.0	31.1	0.5	0.6	0.0	6.2	57.9	100
Mkumbi3 SE6	Spectrum 1	0.7	-0.1	30.6	0.1	0.0	0.0	2.1	66.5	100
	Spectrum 2	0.8	0.0	30.7	0.0	0.0	0.0	2.3	66.1	100
	Spectrum 3	0.7	0.1	30.4	0.0	0.0	0.0	2.2	66.6	100
	Average	0.7	0.0	30.6	0.0	0.0	0.0	2.2	66.4	100
Mkumbi3 SE7	Spectrum 1	0.6	0.0	31.1	0.2	0.0	-0.1	1.9	66.2	100
	Spectrum 2	0.6	-0.1	31.3	0.0	0.0	0.1	1.9	66.1	100
	Spectrum 3	0.6	0.1	30.9	0.1	-0.1	0.0	2.3	66.1	100
	Average	0.6	0.0	31.1	0.1	0.0	0.0	2.0	66.1	100
Mkumbi2 RF4	Spectrum 1	0.4	0.3	30.7	0.1	0.2	0.0	0.1	68.2	100
	Spectrum 2	0.4	0.4	29.8	0.1	0.2	0.1	0.1	68.9	100
	Spectrum 3	0.3	0.5	31.1	-0.1	0.1	0.2	0.2	67.8	100
	Average	0.4	0.4	30.6	0.0	0.1	0.1	0.1	68.3	100
Mkumbi2 RF5	Spectrum 1	0.4	0.5	30.6	0.2	0.1	0.2	1.7	66.4	100
	Spectrum 2	0.8	0.4	30.7	0.3	0.0	0.2	1.6	66.0	100
	Spectrum 3	0.4	0.5	30.6	0.1	0.0	0.2	1.7	66.5	100
	Average	0.6	0.4	30.6	0.2	0.0	0.2	1.6	66.3	100
Mkumbi2 RF6	Spectrum 1	0.5	0.3	30.9	-0.2	0.1	0.2	2.2	65.9	100
	Spectrum 2	0.9	0.6	30.5	0.0	0.1	0.2	2.3	65.5	100
	Spectrum 3	0.5	0.7	30.3	-0.1	0.0	0.2	2.2	66.2	100
	Average	0.7	0.5	30.6	-0.1	0.0	0.2	2.2	65.9	100
Mkumbi2 RF7	Spectrum 1	0.8	0.8	30.0	0.1	0.1	0.4	1.8	66.1	100
	Spectrum 2	0.7	0.4	29.9	0.2	0.1	0.2	2.0	66.5	100
	Spectrum 3	1.0	0.7	29.6	0.0	0.1	0.4	1.7	66.5	100
	Average	0.8	0.7	29.8	0.1	0.1	0.3	1.9	66.3	100
Mkumbi2 RF8	Spectrum 1	1.1	0.9	29.9	0.2	0.1	0.2	2.2	65.5	100
	Spectrum 2	1.1	0.7	30.1	0.1	0.2	0.2	2.2	65.5	100
	Spectrum 3	1.3	0.9	29.4	0.2	0.1	0.4	2.3	65.5	100

	Average	1.1	0.8	29.8	0.1	0.1	0.3	2.2	65.5	100
Mkumbi4 SE8	Spectrum 1	0.6	0.4	30.9	0.2	0.1	0.1	1.6	66.1	100
	Spectrum 2	0.6	0.3	30.4	0.3	0.1	0.1	1.7	66.4	100
	Spectrum 3	0.6	0.4	30.7	0.2	0.1	0.1	1.7	66.2	100
	Average	0.6	0.4	30.7	0.2	0.1	0.1	1.7	66.3	100
Mkumbi4 SE9	Spectrum 1	0.7	0.2	30.9	0.2	0.1	0.1	1.7	66.1	100
	Spectrum 2	0.7	0.0	31.0	0.3	0.1	0.0	1.8	66.2	100
	Spectrum 3	0.8	0.3	31.2	0.0	0.1	0.0	1.7	66.0	100
	Average	0.7	0.1	31.0	0.2	0.1	0.1	1.7	66.1	100
Mkumbi4 SE10	Spectrum 1	0.8	0.9	30.2	0.2	0.2	0.1	2.1	65.6	100
	Spectrum 2	0.7	0.2	31.2	0.0	0.0	0.2	1.9	65.8	100
	Spectrum 3	0.6	0.3	30.6	0.3	0.1	0.2	1.9	65.8	100
	Average	0.7	0.5	30.7	0.2	0.1	0.2	2.0	65.8	100
Mkumbi4 SE11	Spectrum 1	0.6	0.2	30.6	0.1	0.2	0.1	4.0	64.4	100
	Spectrum 2	0.7	0.2	30.3	0.3	0.1	0.2	4.0	64.2	100
	Spectrum 3	0.5	0.1	30.5	0.1	0.1	0.1	3.9	64.7	100
	Average	0.6	0.1	30.4	0.2	0.1	0.1	3.9	64.4	100
Mkumbi4 SE12	Spectrum 1	0.8	0.1	31.2	0.2	0.1	0.0	4.0	63.6	100
	Spectrum 2	0.8	0.0	31.5	0.1	0.0	0.0	3.9	63.7	100
	Spectrum 3	0.7	0.2	31.4	0.0	0.1	0.1	3.9	63.7	100
	Average	0.7	0.1	31.4	0.1	0.1	0.0	3.9	63.7	100
Mkumbi5B RF9	Spectrum 1	0.6	0.1	30.2	0.0	0.1	0.1	0.5	68.5	100
	Spectrum 2	0.6	0.0	30.5	0.1	0.2	-0.1	0.4	68.3	100
	Spectrum 3	0.3	0.2	30.1	-0.5	0.1	0.0	0.4	69.3	100
	Average	0.5	0.1	30.3	-0.1	0.1	0.0	0.4	68.7	100
Mkumbi5B RF10	Spectrum 1	0.3	0.3	30.7	0.2	0.0	0.2	0.6	67.8	100
	Spectrum 2	0.4	0.1	30.8	0.1	0.1	0.0	0.5	68.0	100
	Spectrum 3	0.5	0.1	30.4	0.1	0.1	0.1	0.5	68.3	100
	Average	0.4	0.2	30.6	0.1	0.1	0.1	0.5	68.0	100
Mkumbi5B RF11	Spectrum 1	0.3	0.1	30.6	0.0	0.1	0.1	0.8	68.0	100
	Spectrum 2	0.5	0.1	30.1	0.2	0.2	-0.1	0.5	68.4	100
	Spectrum 3	0.5	0.2	30.9	0.2	0.0	0.1	0.6	67.6	100
	Average	0.4	0.1	30.6	0.1	0.1	0.0	0.6	68.0	100
Mkumbi5B RF12	Spectrum 1	0.1	0.1	31.1	0.0	0.0	0.4	0.3	67.8	100
	Spectrum 2	0.2	0.2	31.8	-0.2	0.1	0.2	0.4	67.2	100
	Spectrum 3	0.2	0.3	30.4	0.1	-0.1	0.3	0.4	68.3	100
	Average	0.2	0.2	31.1	0.0	0.0	0.3	0.4	67.8	100
Mkumbi5B RF13	Spectrum 1	0.7	0.2	29.7	0.1	0.0	0.1	0.4	68.7	100
	Spectrum 2	0.5	0.2	30.1	0.0	0.1	0.1	0.5	68.5	100
	Spectrum 3	0.6	0.1	29.7	0.4	0.1	0.1	0.7	68.3	100
	Average	0.6	0.2	29.9	0.2	0.1	0.1	0.6	68.5	100
TzMkumbi9 RF1	Spectrum 1	0.6	0.4	31.1	0.2	0.1	0.3	2.6	64.6	100
	Spectrum 2	0.5	0.7	31.9	0.1	0.2	0.4	2.5	63.3	100
	Spectrum 3	0.6	0.7	31.4	0.1	0.1	0.3	2.5	63.9	100

	Average	0.6	0.6	31.5	0.1	0.2	0.3	2.5	63.9	100
TzMkumbi9 RF2	Spectrum 1	0.5	0.2	31.5	0.1	0.1	0.1	2.0	65.5	100
	Spectrum 2	0.6	0.3	31.2	0.0	0.0	0.2	1.9	65.6	100
	Spectrum 3	0.4	0.3	30.9	0.3	0.1	0.2	1.9	65.9	100
	Average	0.5	0.3	31.2	0.1	0.1	0.2	1.9	65.6	100
TzMkumbi9 RF3	Spectrum 1	0.3	0.4	30.8	0.0	0.1	0.1	1.9	66.4	100
	Spectrum 2	0.7	0.4	30.3	0.1	0.1	0.2	1.8	66.5	100
	Spectrum 3	0.4	0.3	30.2	0.1	0.1	0.2	1.9	66.8	100
	Average	0.4	0.4	30.4	0.1	0.1	0.2	1.9	66.5	100
TzMkumbi6 SE1	Spectrum 1	1.2	0.4	31.2	0.2	0.1	0.1	2.1	64.5	100
	Spectrum 2	0.9	1.3	32.3	0.5	0.2	0.2	2.0	62.6	100
	Spectrum 3	1.0	1.1	32.9	0.3	0.2	0.2	1.9	61.9	100
	Average	1.0	0.9	32.1	0.3	0.2	0.2	2.0	63.0	100
TzMkumbi6 SE2	Spectrum 1	1.0	0.0	30.6	0.2	0.1	0.0	1.4	66.7	100
	Spectrum 2	1.1	0.0	31.4	0.1	0.1	0.0	1.5	66.1	100
	Spectrum 3	1.1	0.1	31.0	0.0	0.1	0.0	1.2	66.4	100
	Average	1.0	0.0	31.0	0.1	0.1	0.0	1.3	66.4	100

Appendix 5.19: Full results of the EPMA composition of iron droplets of the refining (RF) slags from Ufipa. Note the results are not normalised to 100 wt%

Sample	P	Al	Cu	As	Mo	Ni	Co	S	Mn	Cr	C	Fe	AT
TzMkumbi9 RF1	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.02	0.01	2.28	97.63	99.97
TzMkumbi9 RF1	0.01	0.00	0.05	0.00	0.00	0.00	0.31	0.00	0.02	0.01	2.52	96.23	99.15
TzMkumbi9 RF1	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.48	96.57	100.10
TzMkumbi9 RF1	0.01	0.00	0.02	0.00	0.00	0.00	0.10	0.01	0.00	0.00	3.71	96.51	100.35
TzMkumbi9 RF1	0.01	0.00	0.05	0.00	0.03	0.00	0.00	0.00	0.01	0.00	2.52	96.69	99.31
TzMkumbi9 RF1	0.00	0.00	0.04	0.02	0.01	0.00	0.00	0.00	0.01	0.00	3.09	96.52	99.69
TzMkumbi9 RF1	0.00	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	4.01	95.18	99.26
TzMkumbi9 RF1	0.01	0.00	0.04	0.00	0.00	0.00	0.25	0.00	0.00	0.00		95.53	95.82
TzMkumbi9 RF1	0.00	0.00	0.03	0.00	0.00	0.00	0.02	0.01	0.03	0.00		94.99	95.07
Average	0.00	0.00	0.04	0.00	0.00	0.00	0.07	0.00	0.01	0.00	3.09	96.29	99.52
TzMkumbi9 RF3	0.00	0.04	0.06	0.00	0.01	0.07	0.18	0.00	0.04	0.00	2.97	95.75	99.12
TzMkumbi9 RF3	0.02	0.00	0.03	0.00	0.01	0.02	0.01	0.00	0.01	0.00	3.17	95.21	98.49
TzMkumbi9 RF3	0.00	0.00	0.05	0.00	0.01	0.05	0.73	0.00	0.02	0.00	3.33	95.66	99.86
TzMkumbi9 RF3	0.00	0.00	0.06	0.03	0.01	0.06	0.06	0.00	0.07	0.02	2.29	97.03	99.62
TzMkumbi9 RF3	0.00	0.00	0.05	0.00	0.02	0.06	0.30	0.00	0.03	0.01	3.59	96.04	100.09
TzMkumbi9 RF3	0.01	0.00	0.03	0.00	0.01	0.05	0.00	0.00	0.07	0.00	3.10	95.33	98.60
TzMkumbi9 RF3	0.00	0.00	0.04	0.00	0.00	0.05	0.35	0.01	0.08	0.00		98.00	98.53
Average	0.01	0.01	0.04	0.00	0.01	0.05	0.23	0.00	0.05	0.00	3.08	95.97	99.45
TzMkumbi2 RF8	0.00	0.06	0.03	0.00	0.00	0.06	0.15	0.00	0.06	0.01	4.38	94.64	99.47
TzMkumbi2 RF8	0.01	0.00	0.04	0.00	0.00	0.02	0.00	0.01	0.00	0.00	2.84	94.95	97.86
TzMkumbi2 RF8	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	5.14	94.23	99.41
TzMkumbi2 RF8	0.00	0.00	0.03	0.00	0.00	0.08	0.28	0.00	0.01	0.00	1.84	96.43	98.67

TzMkumbi2 RF8	0.05	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.01	4.65	95.37	100.12
TzMkumbi2 RF8	0.00	0.00	0.04	0.00	0.00	0.00	0.06	0.00	0.01	0.02	5.11	95.32	100.55
TzMkumbi2 RF8	0.00	0.00	0.06	0.00	0.00	0.01	0.36	0.01	0.01	0.00	2.87	96.14	99.45
TzMkumbi2 RF8	0.00	0.00	0.04	0.00	0.01	0.00	0.19	0.00	0.00	0.02	4.22	95.52	100.01
TzMkumbi2 RF8	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.01	0.00	0.00	1.54	98.99	100.58
TzMkumbi2 RF8	0.00	0.00	0.02	0.00	0.02	0.01	0.12	0.00	0.00	0.00	1.52	95.58	97.28
TzMkumbi2 RF8	0.00	0.00	0.03	0.00	0.01	0.01	0.43	0.01	0.00	0.00		100.29	100.79
Average	0.01	0.01	0.03	0.00	0.01	0.02	0.14	0.00	0.01	0.00	3.41	95.92	99.57
TzMkumbi5B RF9	0.01	0.00	0.05	0.11	0.16	1.76	1.03	0.00	0.01	0.00	5.83	92.61	101.58
TzMkumbi5B RF9	0.03	0.11	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	1.87	95.38	98.26
TzMkumbi5B RF9	0.01	0.00	0.03	0.00	0.03	0.32	0.68	0.00	0.00	0.00		93.13	94.20
TzMkumbi5B RF9	0.01	0.00	0.04	0.00	0.02	0.33	0.00	0.00	0.01	0.00		96.16	96.57
TzMkumbi5B RF9	0.00	0.00	0.05	0.00	0.02	0.34	0.00	0.01	0.00	0.00		95.66	96.07
Average	0.01	0.02	0.03	0.02	0.05	0.55	0.34	0.00	0.00	0.00	3.85	94.11	99.16
TzMkumbi5B RF11	0.05	0.00	0.02	0.00	0.00	0.08	0.11	0.00	0.00	0.00	5.76	96.56	102.58
TzMkumbi5B RF11	0.02	0.00	0.02	0.00	0.00	0.15	0.00	0.00	0.00	0.00	5.93	95.78	101.91
TzMkumbi5B RF11	0.01	0.00	0.03	0.00	0.01	0.20	0.27	0.00	0.00	0.00	6.19	92.90	99.61
TzMkumbi5B RF11	0.00	0.00	0.03	0.02	0.03	0.24	0.59	0.01	0.00	0.00	5.37	93.38	99.65
TzMkumbi5B RF11	0.04	0.00	0.05	0.00	0.02	0.20	0.49	0.00	0.00	0.00	4.78	94.59	100.16
TzMkumbi5B RF11	0.00	0.00	0.04	0.00	0.00	0.18	0.00	0.00	0.00	0.00	5.29	94.24	99.76
TzMkumbi5B RF11	0.01	0.00	0.05	0.00	0.01	0.19	0.00	0.01	0.00	0.00	2.21	96.22	98.68
											2.16	96.91	99.07
Average	0.02	0.00	0.03	0.00	0.01	0.18	0.21	0.00	0.00	0.00	5.07	94.81	100.34
TzKamafupa9 RF3	0.11	0.00	0.14	0.77	0.12	2.47	0.17	0.01	0.00	0.00	0.39	96.86	101.05
TzKamafupa9 RF3	0.00	0.00	0.10	0.03	0.05	0.41	0.56	0.01	0.00	0.01	0.06	96.49	97.70
TzKamafupa9 RF3	0.01	1.33	0.11	0.00	0.04	0.83	1.34	0.01	0.03	0.07	3.66	95.16	103.16
TzKamafupa9 RF3	0.00	0.00	0.10	0.00	0.08	1.68	1.17	0.01	0.01	0.01	1.23	96.77	101.05
TzKamafupa9 RF3	0.08	0.00	0.15	0.75	0.12	2.41	1.32	0.01	0.01	0.01	1.72	96.51	103.08
TzKamafupa9 RF3	0.01	0.00	0.18	0.00	0.04	4.31	2.60	0.02	0.02	0.00	1.70	94.30	103.18
Average	0.04	0.22	0.13	0.26	0.08	2.02	1.19	0.01	0.01	0.02	1.46	96.01	101.54
TzKamafupa9 RF1	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.01	1.01	97.68	98.72
TzKamafupa9 RF1	0.00	0.00	0.05	0.00	0.00	0.02	0.42	0.00	0.02	0.00	1.44	96.75	98.70
TzKamafupa9 RF1	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.04	0.01	4.38	95.27	99.76
TzKamafupa9 RF1	0.00	0.00	0.07	0.00	0.00	0.04	0.48	0.00	0.00	0.00	4.60	94.36	99.55
TzKamafupa9 RF1	0.00	0.00	0.06	0.00	0.00	0.09	0.38	0.01	0.01	0.01	3.04	96.84	100.44
TzKamafupa9 RF1	0.01	0.00	0.06	0.03	0.02	0.12	0.20	0.01	0.00	0.00		96.99	97.43
TzKamafupa9 RF1	0.00	0.00	0.02	0.00	0.00	0.05	0.18	0.00	0.04	0.00		98.15	98.44
Average	0.00	0.00	0.05	0.00	0.00	0.04	0.24	0.00	0.02	0.01	2.89	96.31	99.56
TzKamafupa9 RF2	0.01	0.01	0.05	0.00	0.00	0.06	0.31	0.01	0.00	0.00	5.64	92.98	99.06
TzKamafupa9 RF2	0.00	0.00	0.05	0.01	0.00	0.05	0.49	0.01	0.00	0.00	5.02	94.57	100.20
TzKamafupa9 RF2	0.00	0.00	0.04	0.00	0.00	0.10	0.67	0.00	0.01	0.00	5.80	92.43	99.05
TzKamafupa9 RF2	0.00	0.01	0.05	0.00	0.00	0.15	0.38	0.00	0.03	0.00	5.18	93.47	99.27
TzKamafupa9 RF2	0.01	0.00	0.06	0.00	0.00	0.10	0.73	0.00	0.01	0.00	3.08	93.94	97.94
TzKamafupa9 RF2	0.00	0.00	0.05	0.00	0.00	0.08	0.28	0.00	0.01	0.02	5.34	94.04	99.81
TzKamafupa9 RF2	0.02	0.00	0.05	0.00	0.00	0.03	0.31	0.00	0.00	0.00	3.40	95.69	99.50
TzKamafupa9 RF2	0.01	0.00	0.06	0.00	0.00	0.07	0.09	0.00	0.01	0.01	3.54	94.70	98.48

											4.36	93.33	97.69
											3.93	94.57	98.50
											4.67	92.39	97.06
											5.17	94.06	99.24
Average	0.00	0.00	0.05	0.00	0.00	0.08	0.41	0.00	0.01	0.00	4.62	93.98	99.16

Appendix 6: Chapter 6 Appendices

Appendix 6.1: List of smelting (SE), refining (RF), and smithing (ST) sites from Itaka village. Note DWS=distance to water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 52.594'), E (32^0 45.964')	120	295	1554	Kaminyoge Gabriel
2	SE5	S (8^0 52.885'), E (32^0 46.047')	140	64	1554	Michael Sianga
3	SE6	S (8^0 52.484'), E (32^0 45.852')	100	147	1529	Salum Muya
4	RF2	S (8^0 52.621'), E (32^0 46.168')	244	93	1564	Michael Sianga
5	RF3	S (8^0 52.820'), E (32^0 45.905')	150	113	1551	Michael Sianga
6	RF4	S (8^0 52.721'), E (32^0 46.371')	130	201	1591	Michael Sianga
7	ST7	S (8^0 52.350'), E (32^0 46.601')	200	30	1570	Kaminyoge Gabriel
8	**Average (SE)**		**120**	**169**	**1546**	
9	**Average (RF)**		**175**	**136**	**1569**	

Appendix 6.2: List of smelting (SE) and refining (RF) sites from Shihando and Hangomba villages. Note DWS=distance to water source, and HA=Hangomba

S/No.	Site	GPS Location	DWS (m)	Area (m2)	Elevation (m)	Discovered by
1	SE1	S (8^0 51.555'), E (32^0 45.849')	200	50	1541	Edwinus Lyaya
2	SE2	S (8^0 51.575'), E (32^0 47.772')	130	57	1555	Edwinus Lyaya
3	SE3	S (8^0 51.405'), E (32^0 45.733')	164	79	1535	Edwinus Lyaya
4	SE4	S (8^0 51.247'), E (32^0 45.550')	211	102	1534	Edwinus Lyaya
5	SE9	S (8^0 51.888'), E (32^0 45.275')	140	145	1493	Chalamila Ditrick
6	SE11	S (8^0 51.098'), E (32^0 45.062')	252	158	1500	Pamela Felix
7	RF5	S (8^0 51.359'), E (32^0 45.681')	100	113	1539	Rashid Ndongaje
8	RF6	S (8^0 51.324'), E (32^0 45.797')	140	117	1530	Rashid Ndongaje
9	RF7	S (8^0 51.916'), E (32^0 45.307')	167	102	1490	Leticia Tweve
10	RF8	S (8^0 51.886'), E (32^0 45.282')	160	145	1489	Kaminyoge Gabriel
11	RF10	S (8^0 51.936'), E (32^0 45.185')	154	201	1496	Khatibu Tagalile
12	RF12	S (8^0 51.127'), E (32^0 45.265')	167	133	1489	Kaminyoge Gabriel
13	HARF1	S (8^0 51.017'), E (32^0 47.133')	200	133	1390	Salum Muya
14	**Average (SE)**		**183**	**99**	**1526**	
15	**Average (RF)**		**155**	**135**	**1358**	

Appendix 6.3: List of refining (RF) sites from Insane village. Note DWS=distance to water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	RF1	S (8^0 52.681'), E (32^0 45.702')	100	154	1529	Michael Sianga
2	RF2	S (8^0 52.675'), E (32^0 45.702')	120	23	1526	Michael Sianga
3	RF3	S (8^0 53.056'), E (32^0 45.912')	129	53	1533	Michael Sianga
4	RF4	S (8^0 53.187'), E (32^0 45.455')	210	380	1536	Michael Sianga
5	RF5	S (8^0 53.194'), E (32^0 45.454')	209	113	1539	Michael Sianga
6	RF6	S (8^0 53.355'), E (32^0 45.414')	208	314	1538	Michael Sianga
7	**Average (RF)**		**163**	**173**	**1534**	

Appendix 6.4: List of smelting (SE) and refining (RF) sites from Malolo village. Note DWS=distance to water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (9^0 0.044), E (32^0 47.883')	100	42	1487	Thomas Nkota
2	SE2	S (9^0 0.016'), E (32^0 47.226')	100	79	1445	Thomas Nkota
3	RF3A	S (9^0 0.115'), E (32^0 47.251')	200	35	1439	Thomas Nkota
4	RF3B	S (9^0 0.115'), E (32^0 47.251')	200	35	1439	Thomas Nkota
5	**Average (SE)**		**100**	**61**	**1466**	
6	**Average (RF)**		**200**	**35**	**1439**	

Appendix 6.5: List of smelting (SE) and refining (RF) sites from Kapoka village. Note DWS=distance to water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (9^0 5.277'), E (32^0 12.558')	230	1146	1446	Kaminyoge Gabriel
2	SE2	S (9^0 5.342'), E (32^0 12.553')	302	201	1444	Kaminyoge Gabriel
3	SE3	S (9^0 5.412'), E (32^0 12.648')	100	75	1438	Chalamila Ditrick
4	SE4	S (9^0 5.386'), E (32^0 12.648')	130	238	1437	Kaminyoge Gabriel
5	SE6	S (9^0 5.362'), E (32^0 12.601')	100	32	1438	Kaminyoge Gabriel
6	SE8	S (9^0 5.349'), E (32^0 12.671')	120	707	1434	Kaminyoge Gabriel
7	RF5	S (9^0 5.882'), E (32^0 12.646')	139	20	1434	Chalamila Ditrick
8	RF7	S (9^0 5.325'), E (32^0 12.662')	100	28	1434	Kaminyoge Gabriel
9	**Average (SE)**		**164**	**400**	**1439**	
10	**Average (RF)**		**120**	**24**	**1434**	

Appendix 6.6: List of smelting (SE) sites from Iyendwe village. Note DWS=distance to water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (8^0 59.242'), E (32^0 12.299')	302	88	1412	Elias Mkupa
2	SE2	S (8^0 59.289'), E (32^0 12.329')	280	113	1422	Elias Mkupa
3	SE3	S (8^0 58.278'), E (32^0 13.417')	209	113	1422	Khatibu Tagalile
4	**Average (SE)**		**264**	**105**	**1418**	

Appendix 6.7: Full results of the (P) XRF-EDS major and minor oxide concentrations (in wt%) of technical ceramics from Itaka smelting site #1. Note the results are not normalised to 100 wt%, FW=furnace wall, and TYR=tuyère

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzItaka1 FW1	1.14	0.44	36.20	56.44	0.17	0.03	1.08	0.19	1.37	0.01	0.02	0.17	5.63	103
TzItaka1 FW1_r01	1.42	0.42	36.05	56.36	0.17	0.03	1.06	0.18	1.37	0.02	0.02	0.17	5.64	103
TzItaka1 FW1_r02	1.47	0.34	36.16	56.34	0.13	0.03	1.08	0.18	1.36	0.02	0.02	0.17	5.60	103
Average	1.34	0.40	36.14	56.38	0.16	0.03	1.07	0.18	1.37	0.02	0.02	0.17	5.63	103
TzItaka1 FW2	1.47	0.34	37.91	54.78	0.17	0.04	0.93	0.17	1.32	0.02	0.01	0.14	5.62	103
TzItaka1 FW2_r01	1.16	0.31	38.01	54.98	0.17	0.04	0.93	0.17	1.32	0.02	0.01	0.14	5.65	103
TzItaka1 FW2_r02	1.27	0.34	37.91	54.97	0.13	0.04	0.93	0.17	1.31	0.02	0.01	0.14	5.65	103
Average	1.30	0.33	37.94	54.91	0.16	0.04	0.93	0.17	1.32	0.02	0.01	0.14	5.64	103
TzItaka1 FW3	1.26	0.38	39.53	52.83	0.13	0.06	1.06	0.16	1.37	0.02	0.01	0.14	5.93	103
TzItaka1 FW3_r01	1.33	0.30	39.45	52.83	0.18	0.06	1.05	0.17	1.39	0.02	0.01	0.15	5.96	103
TzItaka1 FW3_r02	1.40	0.33	39.40	52.89	0.13	0.06	1.05	0.16	1.37	0.02	0.01	0.14	5.92	103
Average	1.33	0.34	39.46	52.85	0.15	0.06	1.05	0.16	1.38	0.02	0.01	0.14	5.94	103
TzItaka1 TYR1	2.22	0.38	31.47	60.46	0.18	0.02	1.34	0.32	1.33	0.02	0.02	0.21	4.93	103
TzItaka1 TYR1_r01	2.53	0.42	31.40	60.21	0.17	0.02	1.33	0.32	1.33	0.01	0.02	0.21	4.91	103
TzItaka1 TYR1_r02	2.62	0.46	31.32	60.18	0.17	0.02	1.32	0.32	1.33	0.02	0.02	0.21	4.88	103
Average	2.46	0.42	31.40	60.28	0.18	0.02	1.33	0.32	1.33	0.02	0.02	0.21	4.91	103
TzItaka1 TYR2	1.47	0.36	34.78	57.65	0.16	0.02	0.97	0.20	1.39	0.00	0.02	0.15	5.72	103
TzItaka1 TYR2_r01	1.50	0.36	34.80	57.63	0.11	0.02	0.95	0.20	1.39	0.02	0.02	0.15	5.73	103
TzItaka1 TYR2_r02	1.41	0.37	34.70	57.76	0.16	0.02	0.96	0.20	1.39	0.02	0.02	0.15	5.74	103
Average	1.46	0.36	34.76	57.68	0.15	0.02	0.96	0.20	1.39	0.02	0.02	0.15	5.73	103
TzItaka1 TYR3	2.27	0.24	34.42	58.05	0.20	0.03	1.18	0.23	1.26	0.01	0.01	0.17	4.83	103
TzItaka1 TYR3_r01	1.77	0.28	34.49	58.37	0.15	0.03	1.20	0.23	1.30	0.02	0.01	0.17	4.88	103
TzItaka1 TYR3_r02	1.42	0.26	34.59	58.58	0.20	0.04	1.20	0.23	1.29	0.01	0.01	0.17	4.90	103
Average	1.82	0.26	34.50	58.33	0.18	0.03	1.19	0.23	1.28	0.01	0.01	0.17	4.87	103

Appendix 6.8: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of technical ceramics from Itaka smelting site #1. Note the results are not normalised to 100 wt%, FW=furnace wall, and TYR=tuyère

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	Ta2O5	WO3	PbO	Th
TzItaka1 FW1	65	19	32	71	19	51	16	20	333	120	58	24	81	13	13	52	18	27
TzItaka1 FW1_r01	88	19	30	70	19	51	16	20	340	121	57	24	85	13	16	45	20	27
TzItaka1 FW1_r02	81	17	31	70	20	51	16	20	335	121	57	22	81	13	10	54	17	27
Average	78	18	31	71	19	51	16	20	336	121	57	23	82	13	13	50	18	27
TzItaka1 FW2	75	14	23	67	20	45	16	21	332	121	56	22	82	11	13	22	19	26
TzItaka1 FW2_r01	94	12	24	68	21	46	16	21	338	115	57	25	84	9	15	20	19	27
TzItaka1 FW2_r02	112	8	26	66	20	46	16	21	324	119	58	25	83	11	15	17	19	27
Average	94	11	24	67	20	46	16	21	331	118	57	24	83	10	14	20	19	26
TzItaka1 FW3	109	13	23	70	20	54	18	21	357	133	64	23	90	14	17	5	21	29
TzItaka1 FW3_r01	72	17	23	70	22	55	17	22	364	132	67	24	95	16	16	5	20	29
TzItaka1 FW3_r02	70	19	25	74	20	55	17	21	362	136	62	22	87	13	17	5	20	28
Average	84	16	24	71	21	55	17	21	361	134	64	23	90	14	17	5	21	29
TzItaka1 TYR1	47	18	26	75	18	58	24	21	348	123	63	23	85	13	14	62	21	28
TzItaka1 TYR1_r01	79	9	30	74	18	58	24	20	346	118	63	26	86	13	12	54	19	27
TzItaka1 TYR1_r02	88	5	24	74	17	57	23	21	354	125	67	26	86	15	16	51	20	28
Average	71	11	27	74	18	58	23	20	349	122	64	25	86	14	14	56	20	27
TzItaka1 TYR2	85	14	34	68	20	50	16	21	338	120	58	26	87	13	14	48	19	26
TzItaka1 TYR2_r01	90	14	34	69	19	50	16	21	334	123	59	26	89	10	16	50	19	26
TzItaka1 TYR2_r02	78	17	36	66	20	50	16	21	341	120	58	24	92	12	13	57	19	26
Average	84	15	35	68	19	50	16	21	338	121	59	25	89	12	14	51	19	26
TzItaka1 TYR3	64	10	21	70	18	52	21	20	347	120	61	23	80	13	13	17	20	29
TzItaka1 TYR3_r01	79	10	21	70	19	52	21	21	355	127	59	22	82	13	16	14	21	29
TzItaka1 TYR3_r02	53	12	20	73	18	52	22	21	348	125	60	24	80	13	15	17	22	30
Average	65	10	21	71	18	52	21	21	350	124	60	23	81	13	14	16	21	29

Appendix 6.9: Full results of the (P) XRF-EDS major and minor element concentrations (in wt%) of technical ceramics from Itaka smelting site #2. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzItaka2 FW1	1.45	0.25	37.19	55.42	0.18	0.04	1.23	0.17	1.28	0.02	0.01	0.10	5.56	103
TzItaka2 FW1_r01	1.46	0.34	37.14	55.40	0.18	0.04	1.23	0.17	1.28	0.02	0.01	0.09	5.54	103
TzItaka2 FW1_r02	1.55	0.28	37.05	55.47	0.18	0.04	1.23	0.17	1.28	0.02	0.01	0.09	5.52	103
Average	1.49	0.29	37.13	55.43	0.18	0.04	1.23	0.17	1.28	0.02	0.01	0.09	5.54	103
TzItaka2 FW2	1.87	0.32	35.33	57.04	0.20	0.04	1.34	0.18	1.28	0.01	0.01	0.15	5.13	103
TzItaka2 FW2_r01	1.56	0.27	35.63	57.13	0.15	0.05	1.33	0.18	1.27	0.02	0.01	0.15	5.14	103
TzItaka2 FW2_r02	2.08	0.28	35.42	56.79	0.20	0.05	1.32	0.18	1.26	0.01	0.01	0.15	5.13	103
Average	1.84	0.29	35.46	56.99	0.18	0.05	1.33	0.18	1.27	0.02	0.01	0.15	5.13	103
TzItaka2 FW3	1.25	0.38	35.99	56.33	0.13	0.03	1.15	0.16	1.36	0.02	0.02	0.15	5.93	103
TzItaka2 FW3_r01	1.43	0.37	35.86	56.26	0.16	0.03	1.15	0.16	1.36	0.02	0.02	0.15	5.94	103
TzItaka2 FW3_r02	1.60	0.44	35.95	55.95	0.17	0.03	1.15	0.16	1.35	0.02	0.02	0.15	5.90	103

Average	1.43	0.40	35.93	56.18	0.15	0.03	1.15	0.16	1.35	0.02	0.02	0.15	5.92	103
TzItaka2 PTR1	1.47	0.36	33.85	58.62	0.15	0.03	0.96	0.20	1.42	0.02	0.03	0.16	5.63	103
TzItaka2 PTR1_r01	1.56	0.35	33.82	58.53	0.14	0.03	0.97	0.20	1.42	0.02	0.03	0.16	5.65	103
TzItaka2 PTR1_r02	1.23	0.26	33.90	58.85	0.15	0.03	0.98	0.20	1.40	0.02	0.03	0.16	5.70	103
Average	1.42	0.33	33.86	58.67	0.15	0.03	0.97	0.20	1.41	0.02	0.03	0.16	5.66	103
TzItaka2 PTR2	2.85	0.35	29.19	61.41	0.16	0.02	1.18	0.26	1.67	0.02	0.03	0.23	5.52	103
TzItaka2 PTR2_r01	2.35	0.39	29.20	61.79	0.16	0.02	1.19	0.27	1.69	0.02	0.03	0.24	5.56	103
TzItaka2 PTR2_r02	1.93	0.43	29.15	62.15	0.16	0.02	1.18	0.26	1.72	0.02	0.03	0.24	5.61	103
Average	2.38	0.39	29.18	61.78	0.16	0.02	1.18	0.26	1.69	0.02	0.03	0.24	5.56	103
TzItaka2 PTR3	2.39	0.32	30.56	60.16	0.19	0.03	1.35	0.35	1.60	0.02	0.02	0.23	5.69	103
TzItaka2 PTR3_r01	2.10	0.45	30.63	60.19	0.19	0.03	1.37	0.34	1.60	0.02	0.02	0.22	5.71	103
TzItaka2 PTR3_r02	2.58	0.41	30.68	59.86	0.18	0.03	1.34	0.35	1.58	0.02	0.03	0.22	5.63	103
Average	2.36	0.39	30.62	60.07	0.19	0.03	1.35	0.35	1.60	0.02	0.02	0.22	5.68	103
TzItaka2 TYR1	3.47	2.82	23.97	64.22	0.09	0.01	1.60	2.21	0.55	0.01	0.01	0.04	3.93	103
TzItaka2 TYR1_r01	3.54	2.79	23.97	64.16	0.09	0.01	1.59	2.24	0.55	0.01	0.01	0.04	3.93	103
TzItaka2 TYR1_r02	3.15	2.75	24.00	64.54	0.09	0.01	1.60	2.23	0.55	0.01	0.01	0.04	3.95	103
Average	3.39	2.79	23.98	64.31	0.09	0.01	1.59	2.23	0.55	0.01	0.01	0.04	3.94	103
TzItaka2 TYR2	4.25	2.68	24.87	62.74	0.07	0.01	1.16	1.03	0.74	0.02	0.02	0.06	5.29	103
TzItaka2 TYR2_r01	4.13	2.73	24.67	62.99	0.07	0.01	1.17	1.03	0.75	0.02	0.02	0.06	5.30	103
TzItaka2 TYR2_r02	4.47	2.74	24.74	62.63	0.05	0.01	1.14	1.02	0.75	0.02	0.02	0.06	5.27	103
Average	4.28	2.71	24.76	62.79	0.06	0.01	1.16	1.03	0.74	0.02	0.02	0.06	5.29	103
TzItaka2 TYR3	3.19	2.66	24.41	64.20	0.07	0.01	1.64	2.20	0.56	0.01	0.01	0.06	3.93	103
TzItaka2 TYR3_r01	3.27	2.71	24.33	64.11	0.09	0.01	1.65	2.20	0.57	0.01	0.01	0.06	3.93	103
TzItaka2 TYR3_r02	3.29	2.72	24.31	64.13	0.10	0.01	1.65	2.16	0.57	0.01	0.01	0.06	3.93	103
Average	3.25	2.70	24.35	64.15	0.09	0.01	1.65	2.19	0.56	0.01	0.01	0.06	3.93	103

Appendix 6.10: Full results of the (P) XRF-EDS trace element concentrations (in ppm) of technical ceramics from Itaka smelting site #2. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	Ta2O5	WO3	PbO	Th
TzItaka2 FW1	80	15	24	70	20	49	19	24	367	117	86	25	90	12	20	10	21	32
TzItaka2 FW1_r01	90	12	27	63	20	48	19	24	356	115	84	25	90	12	14	7	21	29
TzItaka2 FW1_r02	79	13	24	66	19	48	19	24	361	118	84	27	92	12	17	6	21	31
Average	83	13	25	66	20	48	19	24	361	117	84	25	90	12	17	7	21	31
TzItaka2 FW2	83	12	25	71	20	48	21	23	355	124	83	27	96	11	13	6	25	28
TzItaka2 FW2_r01	86	16	22	75	20	48	21	23	356	119	81	21	87	11	14	11	25	28
TzItaka2 FW2_r02	89	12	21	70	19	49	21	23	355	120	82	23	89	14	16	10	23	29
Average	86	13	23	72	20	48	21	23	355	121	82	24	90	12	14	9	24	28
TzItaka2 FW3	118	12	31	81	21	53	16	21	358	125	82	25	92	12	14	40	18	29
TzItaka2 FW3_r01	87	16	30	80	21	53	16	21	357	118	82	24	95	14	15	40	17	29
TzItaka2 FW3_r02	96	21	31	81	21	53	16	21	358	125	79	22	87	12	13	52	17	28
Average	100	16	30	81	21	53	16	21	358	123	81	24	91	12	14	44	17	29
TzItaka2 PTR1	94	11	40	76	20	50	17	21	338	126	58	29	94	8	14	41	20	26
TzItaka2 PTR1_r01	81	20	40	76	20	50	17	21	335	121	59	30	95	13	14	51	20	27
TzItaka2 PTR1_r02	76	15	41	77	21	50	17	21	353	133	58	29	93	11	13	43	20	28
Average	84	15	40	76	20	50	17	21	342	127	58	29	94	11	14	45	20	27

TzItaka2 PTR2	91	13	27	75	17	57	20	23	334	116	72	28	90	12	16	73	21	26
TzItaka2 PTR2_r01	75	11	27	74	18	58	21	23	336	111	68	29	91	12	16	72	19	27
TzItaka2 PTR2_r02	84	10	27	79	19	58	21	24	351	121	70	30	95	13	15	70	21	27
Average	83	11	27	76	18	57	20	23	340	116	70	29	92	13	16	72	20	27
TzItaka2 PTR3	74	16	39	82	18	64	22	23	327	114	64	27	82	9	13	41	17	26
TzItaka2 PTR3_r01	86	9	42	82	18	64	23	23	334	118	63	28	82	11	12	35	17	28
TzItaka2 PTR3_r02	87	15	38	81	18	63	22	22	336	119	67	31	88	13	16	32	17	26
Average	82	14	40	82	18	64	22	23	332	117	64	28	84	11	14	36	17	27
TzItaka2 TYR1	56	6	25	44	9	48	110	16	74	9	193	14	19	4	7	37	9	9
TzItaka2 TYR1_r01	50	9	26	45	11	47	110	17	71	7	190	14	10	4	5	41	9	9
TzItaka2 TYR1_r02	53	9	26	45	10	48	111	17	72	6	192	13	8	5	7	40	10	9
Average	53	8	26	45	10	47	110	17	72	7	191	14	13	4	6	39	9	9
TzItaka2 TYR2	74	30	66	45	13	40	71	16	122	30	96	19	35	5	9	67	8	10
TzItaka2 TYR2_r01	59	30	60	46	12	40	71	16	119	30	93	17	32	6	8	73	7	10
TzItaka2 TYR2_r02	81	29	64	46	13	39	70	16	120	30	94	17	34	6	9	65	9	10
Average	71	30	63	46	13	39	71	16	120	30	94	17	34	6	8	68	8	10
TzItaka2 TYR3	63	11	26	44	11	47	111	16	64	7	191	14	21	5	5	26	9	9
TzItaka2 TYR3_r01	53	9	25	42	11	47	111	16	65	8	190	13	24	5	6	26	9	8
TzItaka2 TYR3_r02	50	11	26	44	11	47	111	16	63	7	189	13	17	4	4	29	10	9
Average	55	10	26	43	11	47	111	16	64	7	190	13	21	5	5	27	9	9

Appendix 6.11: Full results of the SEM-EDS bulk area composition of the major and minor oxides (in wt%) of the smelting (SE) and refining (RF) slags from Malolo sites. The results are normalised to 100 wt%, and the areas were measured at *x*50

Sample	Area	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	BaO	Ce2O3	Total
TzMalolo3B RF1	Area 1	0.2	0.2	11.8	40.0	0.3	0.7	0.5	1.1	1.2	43.7	0.3	0.0	100
	Area 2	0.3	0.2	11.9	39.0	0.1	0.6	0.5	1.2	1.1	45.2	0.1	0.2	100
	Area 3	0.4	0.1	12.3	38.3	0.2	0.6	0.4	1.4	1.1	45.0	0.1	0.4	100
	Average	0.3	0.2	12.0	39.1	0.2	0.6	0.5	1.2	1.1	44.6	0.1	0.2	100
TzMalolo3B RF2	Area 1	0.4	0.1	11.1	42.0	0.3	0.6	0.5	1.1	1.0	42.6	0.3	0.1	100
	Area 2	0.3	0.1	11.1	42.0	0.1	0.6	0.4	1.1	1.0	43.2	0.1	0.1	100
	Area 3	0.2	0.1	11.4	41.8	0.1	0.5	0.3	1.1	1.1	42.6	0.4	0.1	100
	Average	0.3	0.1	11.2	41.9	0.2	0.6	0.4	1.1	1.0	42.8	0.2	0.1	100
TzMalolo3B RF3	Area 1	0.9	0.3	14.7	24.4	0.7	1.2	1.0	0.5	2.8	52.9	0.2	0.1	
	Area 2	0.5	0.2	13.8	25.2	0.8	1.2	1.1	0.6	3.1	53.1	0.1	0.2	100
	Area 3	0.9	0.1	14.5	24.8	0.7	1.4	0.9	0.4	2.8	53.2	0.2	0.1	100
	Average	0.8	0.2	14.3	24.8	0.7	1.3	1.0	0.5	2.9	53.1	0.2	0.1	100
TzMalolo3B RF4	Area 1	0.2	0.2	13.4	19.8	0.5	0.9	1.2	0.5	1.9	60.9	0.4	0.0	100
	Area 2	0.4	0.1	13.7	20.4	0.9	1.0	1.4	0.3	1.9	60.5	0.2	0.0	100
	Area 3	0.3	0.3	13.2	20.3	0.5	1.0	1.4	0.3	1.9	60.5	0.4	0.0	100
	Average	0.3	0.2	13.4	20.2	0.6	1.0	1.3	0.4	1.9	60.6	0.3	0.0	100
TzMalolo3B RF5	Area 1	0.1	0.0	11.9	38.5	0.1	0.6	0.4	1.1	1.2	45.5	0.3	0.0	100
	Area 2	0.3	0.1	11.3	38.7	-0.1	0.6	0.5	1.2	1.1	46.4	0.3	0.0	100
	Area 3	0.4	0.1	12.8	37.8	0.2	0.6	0.4	1.1	1.1	45.5	0.1	0.0	100

	Average	0.3	0.1	12.0	38.4	0.1	0.6	0.4	1.1	1.1	45.8	0.3	0.0	100
TzMalolo1 SE1	Area 1	0.5	0.4	12.9	30.2	1.2	1.4	2.5	0.5	6.4	43.2	0.8	0.1	100
	Area 2	0.6	0.3	13.5	32.3	0.7	1.5	2.3	0.8	5.9	41.9	0.3	-0.1	100
	Area 3	0.8	0.3	13.4	31.5	0.8	1.3	2.2	0.6	6.3	42.4	0.4	0.1	100
	Average	0.6	0.3	13.3	31.3	0.9	1.4	2.3	0.6	6.2	42.5	0.5	0.0	100
TzMalolo1 SE2	Area 1	0.6	0.1	13.6	28.2	1.0	1.6	1.7	0.6	3.3	48.4	0.4	0.3	100
	Area 2	0.6	0.3	13.4	28.3	0.9	1.7	1.8	0.7	3.5	48.6	0.5	0.0	100
	Area 3	0.8	0.2	12.7	28.7	0.8	1.5	1.9	0.8	3.4	48.6	0.3	0.1	100
	Average	0.7	0.2	13.3	28.4	0.9	1.6	1.8	0.7	3.4	48.5	0.4	0.1	100
TzMalolo1 SE3	Area 1	0.8	0.5	14.7	32.4	1.0	2.2	2.5	0.7	26.2	18.7	0.5	0.0	100
	Area 2	1.1	0.4	14.2	31.0	1.0	2.3	2.4	0.6	26.0	20.5	0.4	0.3	100
	Area 3	0.8	0.3	14.5	31.2	0.9	2.3	2.5	0.6	26.1	20.3	0.3	0.2	100
	Average	0.9	0.4	14.5	31.5	1.0	2.2	2.4	0.6	26.1	19.9	0.4	0.1	100
TzMalolo1 SE4	Area 1	1.2	0.7	19.7	38.3	0.6	3.2	2.8	0.5	13.8	18.9	0.1	0.2	100
	Area 2	1.2	0.7	18.2	40.5	0.4	4.0	3.2	1.0	11.6	19.4	0.0	0.1	100
	Area 3	1.1	0.5	17.9	39.2	0.4	3.0	2.2	0.7	12.9	21.9	0.0	0.3	100
	Average	1.2	0.6	18.6	39.3	0.5	3.4	2.7	0.8	12.8	20.1	0.0	0.2	100
TzMalolo1 SE5	Area 1	1.4	0.4	14.4	33.4	0.4	2.5	2.8	0.4	16.1	28.1	0.1	0.0	100
	Area 2	1.3	0.5	14.4	32.6	0.4	2.4	2.8	0.5	16.4	28.3	0.2	0.2	100
	Area 3	1.1	0.4	14.9	32.8	0.2	2.7	2.7	0.5	15.5	29.1	0.0	0.2	100
	Average	1.3	0.4	14.6	32.9	0.3	2.5	2.7	0.5	16.0	28.5	0.1	0.1	100

Appendix 6.12: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Malolo sites. The results are not normalised to 100 wt%

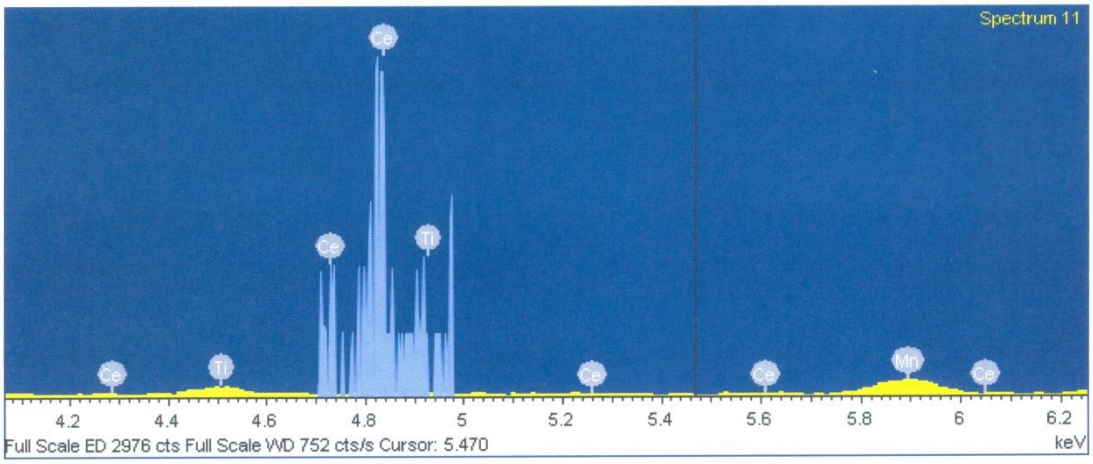
Sample	Co3O4	CuO	ZnO	Ga	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Pr	Nd	Hf	Ta2O5	WO3	Th	U
TzMalolo1 SE1	120	18	69	6	89	30	215	88	1416	22	247	15	20	11	14	25	9	15
TzMalolo1 SE1_r01	120	14	69	7	86	32	208	89	1390	23	247	15	21	11	11	16	9	10
TzMalolo1 SE1_r02	120	18	75	8	89	30	201	89	1409	23	244	15	21	9	20	15	9	11
Average	120	16	71	7	88	31	208	89	1405	23	246	15	21	10	15	19	9	12
TzMalolo1 SE2	130	17	67	11	75	47	286	134	1036	28	418	14	21	10	13	47	10	18
TzMalolo1 SE2_r01	130	19	63	13	74	46	308	151	1054	32	427	15	21	12	11	18	10	22
TzMalolo1 SE2_r02	130	12	63	11	73	48	293	147	1031	33	425	15	21	12	10	48	10	16
Average	130	16	64	12	74	47	296	144	1040	31	423	15	21	11	11	38	10	18
TzMalolo1 SE3	86	16	29	10	142	76	214	114	1645	88	294	15	29	9	10	44	5	13
TzMalolo1 SE3_r01	85	6	29	9	142	77	214	129	1640	87	296	15	56	9	11	41	5	13
TzMalolo1 SE3_r02	86	9	28	10	146	75	211	130	1639	89	291	15	66	9	7	36	5	12
Average	86	10	28	10	144	76	213	124	1641	88	294	15	50	9	9	40	5	12
TzMalolo1 SE4	76	7	44	7	105	71	279	173	598	92	757	13	52	11	11	75	4	9
TzMalolo1 SE4_r01	76	13	50	10	103	69	270	166	598	93	758	13	43	8	13	52	4	11
TzMalolo1 SE4_r02	77	7	52	10	105	70	271	167	594	89	756	13	60	7	8	51	4	17
Average	76	9	49	9	104	70	273	168	597	91	757	13	52	9	11	59	4	12
TzMalolo1 SE5	99	14	43	9	162	59	205	131	346	74	451	13	19	9	14	13	6	19
TzMalolo1 SE5_r01	99	6	39	8	165	58	211	122	343	70	449	14	19	9	14	14	6	16
TzMalolo1 SE5_r02	99	6	39	9	162	58	223	123	345	69	464	13	19	9	15	37	6	11
Average	99	9	40	9	163	58	213	125	345	71	455	13	19	9	14	21	6	15
TzMalolo3B RF1	110	27	22	5	23	20	278	91	663	8	218	14	20	11	14	16	8	15
TzMalolo3B RF1_r01	120	30	18	5	25	18	278	102	678	9	213	14	20	10	21	16	9	10
TzMalolo3B RF1_r02	216	35	20	6	24	19	278	103	671	5	208	14	20	11	10	15	8	9
Average	149	31	20	5	24	19	278	98	671	7	213	14	20	11	15	16	8	11

TzMalolo3B RF2	179	37	26	6	20	19	286	97	719	8	194	14	20	11	12	223	8	10
TzMalolo3B RF2_r01	110	44	28	10	21	19	281	100	720	9	198	14	20	11	12	237	8	10
TzMalolo3B RF2_r02	110	47	28	11	21	20	266	96	716	8	191	14	20	10	13	226	8	17
Average	133	43	27	9	21	19	277	98	718	8	195	14	20	11	12	229	8	12
TzMalolo3B RF3	130	12	59	8	52	28	238	109	452	19	248	14	20	12	9	17	11	12
TzMalolo3B RF3_r01	130	6	56	8	48	28	257	110	451	18	253	14	20	11	9	17	11	9
TzMalolo3B RF3_r02	130	13	62	14	50	29	252	116	441	19	247	14	20	11	18	18	11	21
Average	130	10	59	10	50	29	249	112	448	19	249	14	20	11	12	17	11	14
TzMalolo3B RF4	160	12	43	6	42	22	210	99	391	17	139	14	20	14	17	22	14	9
TzMalolo3B RF4_r01	150	7	36	10	42	22	213	106	394	14	139	14	20	13	11	21	14	15
TzMalolo3B RF4_r02	150	24	41	4	44	22	221	100	387	18	142	15	21	14	23	22	15	10
Average	153	14	40	7	43	22	215	102	391	16	140	14	20	14	17	22	14	11
TzMalolo3B RF5	202	31	22	6	23	19	268	94	677	7	198	13	19	12	12	17	9	11
TzMalolo3B RF5_r01	173	30	16	7	23	19	249	97	690	9	199	13	19	12	12	18	9	8
TzMalolo3B RF5_r02	120	26	23	3	24	18	260	95	684	6	203	14	19	11	23	17	9	17
Average	165	29	20	5	23	18	259	95	684	7	200	13	19	12	16	17	9	12

Appendix 6.13: Full results of the SEM-EDS bulk area composition of the major and minor oxides (in wt%) of the smelting (SE) and refining (RF) slags from Shihando sites. Note that the results are normalised to 100 wt%, and the areas were measured at *x*50

Sample	Area	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	BaO	Ce2O3	Total
TzShihando9 SE1	Area 1	1.4	0.4	13.0	39.3	0.4	2.8	3.1	0.8	4.9	33.6	0.0	0.3	100
	Area 2	1.2	0.4	13.1	40.0	0.2	2.7	2.8	0.7	5.3	33.2	0.3	0.0	100
	Area 3	1.4	0.5	12.9	39.2	0.4	2.7	3.5	0.8	4.8	33.6	0.1	0.0	100
	Average	1.4	0.4	13.0	39.5	0.3	2.7	3.1	0.8	5.0	33.5	0.1	0.1	100
TzShihando9 SE2	Area 1	1.3	0.7	11.5	38.2	0.5	3.0	3.8	0.9	4.6	35.2	0.0	0.3	100
	Area 2	1.2	0.8	11.6	37.9	0.5	2.9	3.6	0.7	4.4	36.5	0.2	0.0	100
	Area 3	1.2	0.6	11.2	37.9	0.3	3.0	3.6	0.7	4.4	37.0	0.1	0.0	100
	Average	1.2	0.7	11.4	38.0	0.4	3.0	3.7	0.8	4.5	36.2	0.1	0.1	100
TzShihando9 SE3	Area 1	1.5	0.9	15.3	42.7	0.2	2.6	3.5	0.9	11.5	19.6	0.9	0.4	100
	Area 2	1.8	0.7	14.8	43.9	0.4	2.8	2.9	1.1	11.3	19.4	0.4	0.5	100
	Area 3	1.3	0.8	15.1	43.1	0.4	2.7	3.2	0.8	11.8	19.7	1.0	0.1	100
	Average	1.5	0.8	15.1	43.2	0.3	2.7	3.2	0.9	11.5	19.6	0.8	0.3	100
TzShihando9 SE4	Area 1	0.8	0.3	13.4	38.1	0.6	1.9	1.9	0.8	7.1	34.1	0.7	0.1	100
	Area 2	1.2	0.5	13.4	37.8	0.6	2.1	2.1	0.9	6.8	33.7	0.8	0.0	100
	Area 3	0.9	0.6	12.8	38.0	0.3	2.1	2.0	0.6	7.9	33.8	0.7	0.1	100
	Average	1.0	0.5	13.2	38.0	0.5	2.0	2.0	0.7	7.3	33.9	0.7	0.1	100
TzShihando9 SE5	Area 1	0.9	0.5	13.9	37.5	0.4	2.0	3.4	1.0	11.3	28.3	0.6	0.3	100
	Area 2	0.8	0.6	13.6	37.5	0.7	2.0	3.4	1.1	10.8	28.9	0.4	0.2	100
	Area 3	0.8	0.7	14.0	38.0	0.4	2.1	3.5	1.0	10.9	27.8	0.7	0.0	100
	Average	0.8	0.6	13.8	37.7	0.5	2.0	3.5	1.1	11.0	28.3	0.6	0.2	100
TzShihando7 RF3	Area 1	1.2	0.1	13.0	36.2	0.3	1.7	0.8	0.5	8.7	36.8	0.2	0.2	100
	Area 2	1.0	-0.2	13.8	36.2	-0.1	2.0	1.1	0.7	8.2	36.4	0.5	0.4	100
	Area 3	0.9	0.2	12.8	36.5	0.3	1.8	0.9	0.7	8.5	36.5	0.3	0.3	100
	Average	1.1	0.0	13.2	36.3	0.2	1.9	1.0	0.6	8.5	36.6	0.3	0.3	100
TzShihando7 RF5	Area 1	1.3	0.3	11.7	39.7	0.3	2.2	1.0	0.7	7.3	35.2	0.0	0.4	100
	Area 2	1.5	0.5	11.3	39.6	0.3	2.1	1.0	0.6	7.2	35.6	0.3	0.2	100
	Area 3	1.4	0.2	11.8	39.9	0.0	2.0	1.0	0.4	7.3	35.4	0.5	0.0	100
	Average	1.4	0.3	11.6	39.7	0.2	2.1	1.0	0.6	7.3	35.4	0.3	0.2	100
TzShihando7 RF6	Area 1	1.3	0.2	12.5	36.8	0.3	1.8	1.0	0.7	7.1	38.0	0.0	0.4	100
	Area 2	1.2	0.1	11.9	38.4	0.2	1.8	1.1	0.6	7.3	37.0	0.5	0.1	100
	Area 3	1.1	0.3	10.8	42.6	0.4	1.6	1.1	0.6	6.7	34.4	0.5	0.0	100
	Average	1.2	0.2	11.8	39.3	0.3	1.7	1.1	0.6	7.1	36.5	0.3	0.1	100
TzShihando7 RF7	Area 1	1.6	0.1	11.6	41.1	0.2	1.9	0.8	0.8	6.4	35.3	0.1	-0.1	100
	Area 2	1.3	0.0	11.3	41.4	0.1	2.0	0.8	0.7	6.8	35.1	0.2	0.2	100
	Area 3	1.3	0.2	11.6	41.2	0.4	2.0	0.9	0.8	6.4	34.8	0.0	0.2	100
	Average	1.4	0.1	11.5	41.3	0.2	2.0	0.8	0.8	6.5	35.1	0.1	0.1	100
TzShihando7 RF8	Area 1	1.3	0.3	12.5	36.8	0.4	1.9	0.9	0.5	9.0	35.6	0.4	0.4	100
	Area 2	1.4	0.2	13.1	36.6	0.1	1.9	0.7	0.5	9.1	35.6	0.4	0.5	100
	Area 3	1.3	0.3	13.5	36.1	0.3	1.8	0.9	0.6	8.8	35.7	0.5	0.5	100
	Average	1.3	0.3	13.0	36.5	0.3	1.9	0.8	0.6	9.0	35.7	0.4	0.5	100

Appendix 6.14: Overlapping spectra of cerium and titanium indicating that there was cerium in the sample, but how much cerium is difficult to achieve through SEM-EDS analysis. The only way to be sure of the concentration of cerium is to analyse one element by one with a WDS such as EPMA



Appendix 6.15: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Shihando sites. The results are not normalised to 100 wt%

Sample	Co3O4	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Pr	Nd	Ta2O5	WO3	U
TzShihando7 RF3	110	15	33	65	43	233	135	1131	59	844	14	34	9	37	14
TzShihando7 RF3_r01	110	14	32	63	43	237	140	1127	59	847	14	41	9	42	10
TzShihando7 RF3_r02	110	18	31	65	43	237	140	1127	61	837	14	38	9	58	10
Average	110	16	32	64	43	236	138	1128	60	843	14	38	9	46	11
TzShihando7 RF5	100	5	28	64	42	217	115	890	45	403	13	20	14	68	20
TzShihando7 RF5_r01	100	12	34	63	42	223	127	894	53	409	14	20	8	72	10
TzShihando7 RF5_r02	100	12	32	62	42	221	122	876	47	404	14	19	15	87	9
Average	100	10	31	63	42	221	121	887	48	406	14	20	12	76	13
TzShihando7 RF6	110	19	30	60	38	208	118	1036	50	805	15	22	7	70	11
TzShihando7 RF6_r01	110	16	30	57	38	210	117	1036	53	802	15	21	15	63	13
TzShihando7 RF6_r02	110	20	31	57	38	208	118	1019	49	790	15	35	9	86	8
Average	110	18	30	58	38	208	118	1030	51	799	15	26	10	73	11
TzShihando7 RF7	100	21	44	59	45	243	134	778	49	374	13	19	9	37	24
TzShihando7 RF7_r01	100	19	48	58	44	244	130	762	46	362	13	19	15	12	10
TzShihando7 RF7_r02	99	16	46	58	44	234	131	782	49	374	14	19	18	12	13
Average	100	19	46	58	44	241	131	774	48	370	13	19	14	20	15
TzShihando7 RF8	110	15	35	63	42	221	131	1112	60	826	14	37	15	17	9
TzShihando7 RF8_r01	110	19	32	63	44	246	129	1151	63	855	14	37	9	27	10
TzShihando7 RF8_r02	110	17	35	62	43	225	126	1131	68	849	14	40	11	53	11
Average	110	17	34	63	43	231	129	1131	63	843	14	38	12	32	10
TzShahando9 SE1	100	10	34	121	37	222	127	663	40	387	13	19	19	50	9
TzShahando9 SE1_r01	100	12	34	124	37	208	120	657	37	393	13	19	8	44	9
TzShahando9 SE1_r02	99	12	29	126	36	216	127	672	35	384	13	19	16	30	9

Average	100	11	32	124	36	215	124	664	37	388	13	19	14	41	9
TzShahando9 SE2	98	10	35	122	37	215	124	676	36	386	13	19	17	12	10
TzShahando9 SE2_r01	98	14	36	118	35	210	116	667	34	379	13	18	9	35	12
TzShahando9 SE2_r02	98	16	38	122	37	216	109	670	37	381	13	19	14	30	11
Average	98	13	36	121	36	214	116	671	36	382	13	19	13	25	11
TzShahando9 TSE3	63	12	50	144	54	285	152	1961	77	751	13	66	15	59	9
TzShahando9 TSE3_r01	64	11	50	148	54	281	161	1981	81	774	14	47	11	61	10
TzShahando9 TSE3_r02	63	7	52	146	55	266	151	1964	80	766	13	67	20	69	10
Average	63	10	51	146	54	277	155	1969	79	763	13	60	16	63	10
TzShahando9 SE4	100	9	63	104	33	242	115	2146	35	335	15	35	17	24	20
TzShahando9 SE4_r01	100	11	61	103	32	239	118	2137	33	334	15	39	6	58	10
TzShahando9 SE4_r02	100	6	67	102	33	236	128	2130	35	334	14	32	20	67	10
Average	100	9	64	103	33	239	120	2138	35	334	15	35	14	50	13
TzShahando9 SE5	95	17	26	172	50	272	158	1953	66	502	15	49	6	11	11
TzShahando9 SE5_r01	94	9	25	172	51	268	146	1925	63	488	14	60	18	11	16
TzShahando9 SE5_r02	94	15	24	170	49	276	143	1919	69	495	14	60	9	31	10
Average	94	13	25	171	50	272	149	1932	66	495	14	56	11	18	12

Appendix 6.16: Full results of the SEM-EDS bulk area composition of the major and minor oxides (in wt%) of the smelting (SE) and refining (RF) slags from Itaka sites. Note that the results are normalised to 100 wt%, and the areas were measured at *x*50

Sample	Area	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	BaO	Ce2O3	Total
TzItaka1 SE1	Area 1	1.1	0.5	11.3	41.2	0.3	2.0	1.6	0.8	3.7	37.2	0.3	0.2	100
	Area 2	1.2	0.3	11.5	42.2	0.2	2.0	1.6	0.7	4.1	36.1	0.1	0.2	100
	Area 3	1.4	0.4	11.1	40.7	0.4	1.8	1.6	0.5	3.9	37.4	0.4	0.1	100
	Average	1.2	0.4	11.3	41.4	0.3	1.9	1.6	0.7	3.9	36.9	0.3	0.2	100
TzItaka1 SE2	Area 1	1.2	0.4	12.5	38.7	0.6	2.1	1.8	0.7	3.1	38.4	0.1	0.5	100
	Area 2	1.2	0.4	12.1	39.3	0.4	2.1	1.8	0.7	3.4	38.0	0.4	0.0	100
	Area 3	1.4	0.3	12.3	40.2	0.4	2.0	1.7	0.7	3.6	36.7	0.5	0.1	100
	Average	1.2	0.4	12.3	39.4	0.5	2.1	1.8	0.7	3.4	37.7	0.4	0.2	100
TzItaka1 SE3	Area 1	1.2	0.3	14.1	33.2	0.5	1.9	1.4	0.6	18.0	27.4	1.4	0.1	100
	Area 2	1.2	0.2	13.5	33.8	0.2	1.8	1.4	0.6	17.8	27.9	1.2	0.3	100
	Area 3	1.0	0.3	13.6	34.0	0.4	1.9	1.5	0.6	17.7	27.3	1.5	0.0	100
	Average	1.1	0.3	13.8	33.6	0.4	1.9	1.5	0.6	17.9	27.5	1.4	0.1	100
TzItaka1 SE4	Area 1	1.4	0.5	13.0	39.7	0.6	2.4	2.4	0.7	8.5	30.2	0.1	0.3	100
	Area 2	1.4	0.6	13.4	42.1	0.6	2.7	2.6	0.6	9.3	26.4	0.6	-0.1	100
	Area 3	1.1	0.4	12.9	40.8	0.4	2.5	2.4	0.8	9.1	29.7	0.2	0.0	100
	Average	1.3	0.5	13.1	40.9	0.5	2.5	2.5	0.7	9.0	28.8	0.3	0.1	100
TzItaka1 SE5	Area 1	1.3	0.3	11.1	40.2	0.4	1.8	1.5	0.7	3.7	38.8	0.1	0.4	100
	Area 2	1.1	0.4	11.2	40.1	0.4	1.7	1.4	0.7	3.9	38.7	0.3	0.1	100
	Area 3	1.1	0.5	10.7	40.7	0.3	1.7	1.4	0.7	3.8	38.8	0.1	0.2	100
	Average	1.2	0.4	11.0	40.3	0.4	1.8	1.4	0.7	3.8	38.8	0.1	0.2	100
TzItaka2 RF3	Area 1	0.7	0.2	11.6	33.2	0.5	1.2	1.3	1.1	3.8	45.9	0.5	0.2	100

	Area 2	0.6	0.1	11.8	35.3	0.5	1.1	1.1	1.2	3.6	44.3	0.2	0.0	100
	Area 3	0.4	0.3	11.7	34.0	0.3	1.3	1.1	1.1	3.7	45.4	0.4	0.1	100
	Average	0.6	0.2	11.7	34.2	0.5	1.2	1.2	1.1	3.7	45.2	0.4	0.1	100
TzItaka2 RF4	Area 1	1.3	0.1	13.4	39.3	0.1	1.9	0.9	0.6	6.5	34.9	0.5	0.4	100
	Area 2	1.7	0.2	13.0	39.5	0.1	1.9	0.8	0.6	7.1	34.6	0.4	0.1	100
	Area 3	1.5	0.3	13.0	39.6	0.1	2.0	0.8	0.7	7.4	33.8	0.0	0.4	100
	Average	1.5	0.2	13.2	39.5	0.1	2.0	0.8	0.7	7.0	34.4	0.3	0.3	100
TzItaka2 RF5	Area 1	1.0	0.4	14.5	35.9	0.4	1.9	0.9	0.8	8.2	35.1	0.3	0.3	100
	Area 2	1.0	0.3	13.6	35.4	0.2	1.7	0.9	0.9	7.7	37.8	0.5	0.0	100
	Area 3	1.1	0.2	14.2	37.8	0.2	1.9	1.0	0.8	9.0	33.1	0.7	-0.1	100
	Average	1.0	0.3	14.1	36.4	0.3	1.8	0.9	0.8	8.3	35.3	0.5	0.1	100
TzItaka2 RF6	Area 1	1.5	0.2	12.9	37.2	0.0	1.7	1.0	0.8	6.3	38.0	0.4	0.1	100
	Area 2	1.3	0.3	12.9	37.0	0.0	1.8	1.2	0.6	6.4	37.9	0.3	0.2	100
	Area 3	1.3	0.2	12.1	37.1	0.3	1.6	1.0	0.8	7.4	37.2	0.2	0.5	100
	Average	1.4	0.3	12.7	37.1	0.1	1.7	1.1	0.8	6.7	37.7	0.3	0.2	100
TzItaka2 RF7	Area 1	1.3	0.3	13.2	36.5	0.6	1.8	1.0	0.7	6.4	37.4	0.2	0.4	100
	Area 2	1.6	0.1	13.2	36.9	0.0	1.9	1.1	0.7	6.8	37.1	0.4	0.1	100
	Area 3	1.5	0.2	13.3	36.5	0.0	2.0	1.1	0.6	6.1	37.9	0.5	0.1	100
	Average	1.5	0.2	13.2	36.6	0.2	1.9	1.1	0.7	6.4	37.5	0.4	0.2	100

Appendix 6.17: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting (SE) and refining (RF) slags from Itaka sites. The results are not normalised to 100 wt%

Sample	Co3O4	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Pr	Nd	Ta2O5	WO3	U
TzItaka1 SE1	100	11	32	57	40	214	132	773	47	720	14	21	18	41	13
TzItaka1 SE1_r01	100	9	33	57	38	236	129	766	52	732	14	19	9	44	16
TzItaka1 SE1_r02	100	8	31	57	41	225	135	776	46	737	14	20	8	49	14
Average	100	9	32	57	40	225	132	772	48	730	14	20	12	45	14
TzItaka1 SE2	100	10	25	77	33	250	136	1063	29	836	14	22	20	13	13
TzItaka1 SE2_r01	100	10	27	78	31	249	134	1049	29	828	14	19	22	13	10
TzItaka1 SE2_r02	100	10	26	78	31	259	134	1062	30	830	14	20	25	12	18
Average	100	10	26	78	32	252	134	1058	29	831	14	20	22	13	14
TzItaka1 SE3	99	5	70	158	44	221	139	3855	52	640	17	50	13	39	14
TzItaka1 SE3_r01	100	7	62	157	44	232	133	3883	52	642	17	59	14	14	12
TzItaka1 SE3_r02	98	9	64	154	44	235	137	3807	51	637	17	44	10	14	12
Average	99	7	65	156	44	229	137	3848	52	640	17	51	13	22	13
TzItaka1 SE4	96	12	31	116	39	220	126	957	43	461	14	20	7	40	7
TzItaka1 SE4_r01	96	11	34	121	37	219	125	946	41	462	14	19	8	58	13
TzItaka1 SE4_r02	96	8	30	118	38	219	115	959	43	465	13	19	14	19	9
Average	96	10	32	118	38	219	122	954	43	462	14	19	10	39	9
TzItaka1 SE5	100	5	29	52	37	211	120	702	41	662	13	33	18	13	9
TzItaka1 SE5_r01	100	14	32	55	37	209	119	715	40	658	14	19	8	36	10
TzItaka1 SE5_r02	100	8	35	50	37	209	124	721	43	667	13	28	18	14	10
Average	100	9	32	52	37	209	121	713	41	662	13	26	15	21	9

TzItaka2 RF3	120	22	32	72	31	249	118	1129	24	266	14	20	9	27	12
TzItaka2 RF3_r01	120	15	30	68	31	262	132	1154	27	273	15	21	10	54	10
TzItaka2 RF3_r02	120	7	29	70	31	265	128	1138	29	270	14	20	24	15	12
Average	120	15	30	70	31	259	126	1140	27	270	14	20	15	32	11
TzItaka2 RF4	100	9	35	63	37	220	112	1315	42	557	13	29	13	41	16
TzItaka2 RF4_r01	100	10	35	63	38	231	132	1370	47	582	14	20	7	40	10
TzItaka2 RF4_r02	99	8	34	64	38	215	119	1336	45	564	14	21	8	23	12
Average	99.67	9	34	63	38	222	121	1340	44	567	14	24	10	35	12
TzItaka2 RF5	110	15	36	77	40	227	126	1551	48	662	14	46	15	61	14
TzItaka2 RF5_r01	110	9	30	76	40	230	134	1578	51	680	15	34	9	58	11
TzItaka2 RF5_r02	110	16	27	78	41	222	122	1558	52	688	15	37	9	35	16
Average	110	13	31	77	40	227	127	1562	50	677	15	39	11	52	14
TzItaka2 RF6	110	7	31	60	37	213	123	1298	48	672	14	24	16	33	12
TzItaka2 RF6_r01	110	12	25	58	38	205	121	1283	43	658	14	35	9	41	9
TzItaka2 RF6_r02	110	10	25	59	37	211	118	1274	48	650	14	30	17	13	11
Average	110	10	27	59	37	209	121	1285	47	660	14	30	14	29	11
TzItaka2 RF7	110	8	24	61	38	203	127	1284	48	648	14	32	14	13	18
TzItaka2 RF7_r01	110	10	22	59	37	211	117	1278	46	658	14	36	9	33	10
TzItaka2 RF7_r02	110	6	26	60	36	198	120	1252	44	633	14	25	19	13	10
Average	110	8	24	60	37	204	122	1271	46	646	14	31	14	20	13

Appendix 6.18: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Malolo sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Ce2O3	Total
TzMalolo1 SE1	0.7	0.3	12.7	32.5	0.7	1.5	2.5	0.7	6.1	42.0	0.4	100
TzMalolo1 SE2	0.9	0.2	12.4	29.0	0.9	1.7	1.9	0.9	3.5	48.5	0.2	100
TzMalolo1 SE3	0.9	0.4	14.0	32.4	1.0	2.2	2.6	0.7	26.3	19.2	0.3	100
TzMalolo1 SE4	1.3	0.4	17.0	39.1	0.3	2.5	2.2	0.7	13.6	22.6	0.3	100
TzMalolo1 SE5	1.2	0.5	14.0	32.4	0.5	2.6	2.9	0.6	15.7	29.4	0.1	100
TzMalolo3B RF1	0.1	0.1	12.3	39.5	0.2	0.7	0.5	1.2	1.1	44.7	0.0	100
TzMalolo3B RF2	0.2	0.2	11.5	42.2	0.1	0.6	0.4	1.2	1.0	42.5	0.1	100
TzMalolo3B RF3	0.8	0.3	14.2	24.9	0.7	1.4	1.0	0.6	3.0	53.2	0.0	100
TzMalolo3B RF4	0.4	0.2	12.3	21.1	0.5	0.9	1.4	0.5	2.0	60.6	0.0	100
TzMalolo3B RF5	0.2	0.0	12.1	38.4	0.2	0.6	0.5	1.3	1.2	45.6	0.0	100

Appendix 6.19: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Shihando sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Ce2O3	Total
TzShihando9 SE1	1.4	0.5	13.0	39.4	0.3	2.9	3.2	0.7	4.6	33.8	0.3	100
TzShihando9 SE2	1.3	0.7	11.3	38.2	0.3	2.9	3.7	0.8	4.4	36.4	0.2	100
TzShihando9 SE3	1.5	0.7	15.1	44.3	0.4	3.0	3.0	1.2	11.6	18.7	0.6	100
TzShihando9 SE4	0.9	0.4	13.3	38.2	0.5	2.1	2.2	1.0	7.9	33.2	0.3	100
TzShihando9 SE5	0.7	0.6	14.0	37.9	0.4	2.1	3.6	1.1	11.0	28.2	0.3	100
TzShihando7 RF3	1.0	0.3	12.4	36.4	0.1	1.8	1.0	0.7	9.0	37.3	0.2	100
TzShihando7 RF5	1.2	0.2	12.0	40.3	0.2	2.0	1.1	0.7	7.2	34.9	0.2	100
TzShihando7 RF6	1.2	0.2	11.7	38.0	0.2	1.8	1.1	0.7	7.4	37.4	0.3	100
TzShihando7 RF7	1.3	0.2	11.6	42.1	0.0	2.0	0.8	0.7	6.5	34.6	0.1	100
TzShihando7 RF8	1.2	0.2	14.0	36.1	0.2	2.0	0.9	0.8	8.6	35.8	0.3	100

***Appendix 6.20*:** SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) and refining (RF) slags from Itaka sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Ce2O3	Total
TzItaka1 SE1	1.2	0.4	11.2	41.8	0.2	1.9	1.5	0.7	4.4	36.3	0.4	100
TzItaka1 SE2	1.2	0.4	12.3	39.6	0.3	2.0	1.8	0.9	3.2	38.0	0.3	100
TzItaka1 SE3	1.1	0.2	13.8	34.6	0.3	1.9	1.6	1.1	17.4	27.5	0.6	100
TzItaka1 SE4	1.3	0.6	12.4	40.6	0.5	2.4	2.5	0.7	8.8	29.9	0.2	100
TzItaka1 SE5	1.3	0.3	11.3	40.4	0.3	1.8	1.4	0.7	3.8	38.5	0.3	100
TzItaka2 RF3	0.5	0.4	11.8	36.5	0.5	1.2	1.2	1.3	4.0	42.4	0.2	100
TzItaka2 RF4	1.4	0.2	12.8	40.5	0.1	2.0	0.8	0.8	7.2	34.0	0.3	100
TzItaka2 RF5	0.8	0.4	13.1	36.9	0.3	1.9	1.2	1.1	8.9	34.9	0.5	100
TzItaka2 RF6	1.1	0.2	12.7	37.3	0.1	1.7	1.1	0.9	6.7	37.6	0.5	100
TzItaka2 RF7	1.4	0.2	12.8	36.9	0.1	1.8	1.1	0.9	7.1	37.5	0.3	100

Appendix 6.21: Full results of the SEM-EDS chemical composition (in wt%) of fayalitic crystals in the smelting (SE) and refining (RF) slags from Mbozi. Note the results are normalised to 100 wt%

Sample	Spectrum	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Total
TzItaka1 SE1	Spectrum 1	1.4	0.0	31.1	-0.2	0.0	0.2	0.1	6.6	60.6	100
	Spectrum 2	1.2	0.1	30.9	0.2	0.0	0.2	0.1	5.7	61.6	100
	Spectrum 3	1.2	0.4	32.0	0.3	0.3	0.2	0.2	5.9	59.3	100
	Average	1.3	0.2	31.4	0.1	0.1	0.2	0.2	6.1	60.5	100
TzItaka1 SE2	Spectrum 1	1.1	0.2	31.0	0.1	0.0	0.2	0.1	4.8	62.5	100
	Spectrum 2	1.2	0.3	31.8	0.1	0.1	0.2	0.1	4.5	61.6	100
	Spectrum 3	1.5	0.3	31.8	0.2	0.1	0.2	0.2	5.0	60.6	100
	Average	1.3	0.2	31.5	0.1	0.1	0.2	0.1	4.8	61.6	100
TzItaka1 SE3	Spectrum 1	0.8	0.3	31.6	0.1	-0.1	0.2	0.2	28.5	38.4	100
	Spectrum 2	1.0	0.2	30.9	0.1	0.0	0.2	0.3	29.2	38.2	100
	Spectrum 3	0.9	0.1	31.3	0.1	0.0	0.2	0.1	29.0	38.2	100
	Average	0.9	0.2	31.2	0.1	0.0	0.2	0.2	28.9	38.3	100
TzItaka1 SE4	Spectrum 1	1.7	0.5	31.0	0.3	0.2	0.4	0.2	11.5	54.2	100
	Spectrum 2	1.9	0.5	31.3	0.3	0.1	0.5	0.1	11.0	54.4	100
	Spectrum 3	1.7	0.6	31.3	0.3	0.1	0.4	0.3	11.2	54.2	100
	Average	1.8	0.5	31.2	0.3	0.1	0.4	0.2	11.2	54.3	100
TzItaka1 SE5	Spectrum 1	0.69	1.48	32.96	0.01	0.43	0.39	0.28	5.07	58.69	100
	Spectrum 2	0.61	2.77	34.43	0.14	0.58	0.49	0.32	4.76	55.91	100
	Spectrum 3	0.75	1.70	32.71	0.02	0.42	0.33	0.33	4.87	58.86	100
	Average	0.68	1.98	33.37	0.06	0.48	0.41	0.31	4.90	57.82	100
TzItaka2 RF3	Spectrum 1	0.9	0.3	30.2	0.4	0.0	0.1	0.3	4.3	63.6	100
	Spectrum 2	1.1	0.1	30.5	0.4	0.0	0.1	0.2	4.6	63.1	100
	Spectrum 3	1.0	0.3	30.5	0.4	-0.1	0.1	0.3	4.4	63.0	100
	Average	1.0	0.2	30.4	0.4	0.0	0.1	0.2	4.4	63.2	100
TzItaka2 RF4	Spectrum 1	0.9	0.3	31.8	0.1	0.0	0.1	0.2	9.8	56.8	100
	Spectrum 2	0.6	0.1	31.3	0.1	0.0	0.1	0.0	9.8	58.0	100
	Spectrum 3	0.9	0.3	31.5	0.0	0.0	0.1	0.2	10.0	56.9	100
	Average	0.8	0.3	31.5	0.1	0.0	0.1	0.1	9.9	57.2	100
TzItaka2 RF5	Spectrum 1	1.0	0.3	30.8	0.2	0.1	0.1	0.3	13.3	54.0	100
	Spectrum 2	0.8	0.4	30.7	0.4	0.1	0.1	0.3	12.8	54.4	100
	Spectrum 3	0.8	0.2	31.1	0.3	0.0	0.1	0.1	12.8	54.7	100
	Average	0.9	0.3	30.8	0.3	0.1	0.1	0.2	12.9	54.3	100
TzItaka2 RF6	Spectrum 1	0.4	0.2	30.4	0.0	0.0	0.1	0.1	10.3	58.4	100
	Spectrum 2	0.9	0.1	31.2	0.0	0.1	0.1	0.2	9.9	57.5	100
	Spectrum 3	0.5	0.2	30.6	0.1	0.0	0.1	0.2	10.4	58.0	100
	Average	0.6	0.2	30.7	0.1	0.0	0.1	0.2	10.2	58.0	100
TzItaka2 RF7	Spectrum 1	0.6	0.3	30.3	0.1	0.0	0.1	0.1	9.7	58.8	100
	Spectrum 2	0.7	0.5	30.2	0.2	0.0	0.2	0.2	10.4	57.5	100
	Spectrum 3	0.8	0.3	30.2	0.1	0.1	0.1	0.2	10.4	57.7	100

	Average	0.7	0.4	30.3	0.1	0.0	0.1	0.2	10.2	58.0	100
TzMalolo3B RF1	Spectrum 1	0.5	0.4	31.2	0.3	0.0	0.1	0.5	1.1	65.9	100
	Spectrum 2	0.4	0.3	30.7	0.1	0.0	0.1	0.6	1.3	66.6	100
	Spectrum 3	0.5	0.8	30.7	0.1	0.1	0.0	0.5	1.0	66.3	100
	Average	0.5	0.5	30.9	0.2	0.0	0.1	0.5	1.1	66.3	100
TzMalolo3B RF2	Spectrum 1	0.2	11.9	42.1	0.1	0.7	0.3	1.4	1.0	42.4	100
	Spectrum 2	0.2	11.6	42.6	0.2	0.7	0.4	1.4	1.0	42.0	100
	Spectrum 3	0.1	11.9	42.4	-0.1	0.6	0.4	1.2	1.2	42.3	100
	Average	0.1	11.8	42.3	0.1	0.7	0.4	1.3	1.1	42.2	100
TzMalolo3B RF3	Spectrum 1	0.5	0.5	29.6	0.2	0.0	0.2	0.1	4.5	64.5	100
	Spectrum 2	0.6	0.5	29.5	0.3	0.1	0.2	0.3	4.2	64.3	100
	Spectrum 3	0.5	0.4	29.2	0.3	0.0	0.3	0.3	4.6	64.4	100
	Average	0.5	0.5	29.4	0.3	0.0	0.2	0.2	4.4	64.4	100
TzMalolo3B RF4	Spectrum 1	0.3	0.5	29.5	0.5	0.0	0.6	0.2	2.9	65.5	100
	Spectrum 2	0.7	0.3	30.6	0.2	0.0	0.4	0.0	3.1	64.6	100
	Spectrum 3	0.5	0.3	30.3	0.4	0.0	0.7	0.1	3.3	64.6	100
	Average	0.5	0.4	30.1	0.4	0.0	0.5	0.1	3.1	64.9	100
TzMalolo3B RF5	Spectrum 1	0.5	0.3	30.0	0.1	0.0	0.1	0.3	1.6	67.1	100
	Spectrum 2	0.4	0.3	30.1	0.0	0.0	0.0	0.2	1.8	67.1	100
	Spectrum 3	0.3	0.3	30.0	0.0	0.0	0.0	0.3	1.7	67.3	100
	Average	0.4	0.3	30.0	0.0	0.0	0.0	0.3	1.7	67.2	100
TzMalolo1 SE1	Spectrum 1	0.7	0.0	30.3	0.3	0.1	0.3	0.3	9.8	58.2	100
	Spectrum 2	0.5	0.3	30.3	0.4	0.0	0.2	0.1	10.0	58.3	100
	Spectrum 3	0.5	0.2	30.2	0.1	0.0	0.3	0.0	9.6	58.9	100
	Average	0.6	0.2	30.3	0.2	0.1	0.3	0.1	9.8	58.5	100
TzMalolo1 SE2	Spectrum 1	0.7	0.3	30.1	0.2	0.0	0.4	0.1	5.3	62.9	100
	Spectrum 2	1.0	0.3	30.2	0.0	-0.1	0.3	0.2	5.8	62.2	100
	Spectrum 3	0.5	0.2	30.9	0.2	0.0	0.3	0.0	5.3	62.6	100
	Average	0.7	0.2	30.4	0.1	0.0	0.4	0.1	5.5	62.6	100
TzMalolo1 SE3	Spectrum 1	0.6	0.0	30.1	0.5	0.0	0.2	0.1	38.3	30.2	100
	Spectrum 2	1.0	0.1	30.4	0.5	0.0	0.5	0.2	41.6	25.7	100
	Spectrum 3	0.5	0.3	30.2	0.2	0.0	0.2	0.0	38.1	30.4	100
	Average	0.7	0.2	30.2	0.4	0.0	0.3	0.1	39.4	28.8	100
TzMalolo1 SE4	Spectrum 1	1.3	0.4	31.2	0.3	0.1	0.3	0.2	26.7	39.6	100
	Spectrum 2	1.2	0.2	30.9	0.2	0.1	0.3	0.1	27.3	39.8	100
	Spectrum 3	1.2	1.1	32.3	0.2	0.4	0.4	0.2	26.4	37.8	100
	Average	1.2	0.5	31.5	0.2	0.2	0.3	0.2	26.8	39.0	100
TzMalolo1 SE5	Spectrum 1	1.7	0.1	30.8	0.1	0.0	1.0	0.2	26.7	39.5	100
	Spectrum 2	1.4	0.3	30.8	0.2	0.0	0.9	0.0	26.6	39.8	100
	Spectrum 3	1.4	0.2	30.9	0.1	0.1	0.9	0.0	26.5	39.9	100
	Average	1.5	0.2	30.8	0.1	0.0	0.9	0.1	26.6	39.7	100
TzShihando9 SE1	Spectrum 1	1.8	0.1	31.8	-0.1	0.1	0.5	0.1	8.7	57.0	100
	Spectrum 2	2.7	0.4	31.7	0.0	0.2	0.5	0.2	8.5	56.0	100
	Spectrum 3	1.8	1.0	32.4	0.3	0.3	0.6	0.1	8.2	55.3	100
	Average	2.1	0.5	31.9	0.1	0.2	0.6	0.1	8.5	56.1	100
TzShihando9 SE2	Spectrum 1	2.3	1.0	31.1	0.1	0.4	0.7	0.1	6.6	57.7	100

	Spectrum 2	2.1	0.3	30.3	0.3	0.1	0.7	0.1	6.8	59.4	100
	Spectrum 3	1.7	0.2	30.5	0.0	0.0	0.5	0.0	6.7	60.3	100
	Average	2.0	0.5	30.6	0.1	0.2	0.6	0.1	6.7	59.1	100
TzShihando9 SE3	Spectrum 1	2.1	0.2	31.4	0.2	0.1	0.4	0.2	25.2	40.3	100
	Spectrum 2	1.7	0.6	31.8	0.2	0.3	0.5	0.3	25.0	39.7	100
	Spectrum 3	2.0	0.1	30.8	0.0	0.0	0.4	0.2	26.0	40.4	100
	Average	1.9	0.3	31.3	0.1	0.1	0.5	0.2	25.4	40.1	100
TzShihando9 SE4	Spectrum 1	1.1	0.1	31.4	0.0	0.0	0.2	0.2	11.8	55.1	100
	Spectrum 2	1.0	0.2	31.0	0.2	0.1	0.3	0.2	11.4	55.7	100
	Spectrum 3	1.0	0.3	31.0	0.3	0.1	0.2	0.1	11.5	55.5	100
	Average	1.0	0.2	31.1	0.2	0.1	0.2	0.2	11.6	55.4	100
TzShihando9 SE5	Spectrum 1	2.7	0.1	31.0	0.0	0.1	0.4	0.1	20.0	45.7	100
	Spectrum 2	3.0	0.1	31.5	0.1	0.1	0.4	0.1	20.1	44.7	100
	Spectrum 3	2.8	0.0	30.8	0.1	0.0	0.5	0.1	20.7	45.0	100
	Average	2.8	0.1	31.1	0.1	0.0	0.4	0.1	20.3	45.1	100
TzShihando7 RF3	Spectrum 1	0.3	0.5	30.9	-0.1	0.0	0.2	0.2	12.5	55.6	100
	Spectrum 2	0.6	0.5	29.3	0.3	0.0	0.2	0.1	12.6	56.3	100
	Spectrum 3	0.7	0.2	31.1	-0.1	0.0	0.2	0.1	12.2	55.5	100
	Average	0.5	0.4	30.4	0.0	0.0	0.2	0.1	12.4	55.8	100
TzShihando7 RF5	Spectrum 1	0.7	0.1	31.9	0.2	0.2	0.1	0.4	10.7	55.8	100
	Spectrum 2	0.6	0.7	31.4	-0.3	0.1	0.3	0.4	11.2	55.6	100
	Spectrum 3	0.7	1.7	33.6	0.0	0.7	0.4	0.0	10.1	52.8	100
	Average	0.7	0.8	32.3	0.0	0.3	0.3	0.3	10.7	54.7	100
TzShihando7 RF6	Spectrum 1	0.6	0.2	31.8	0.1	0.0	0.0	0.1	10.8	56.4	100
	Spectrum 2	0.3	0.1	31.0	0.3	0.0	0.1	0.3	9.9	58.0	100
	Spectrum 3	0.5	0.3	30.7	0.3	0.0	0.2	0.1	10.1	57.8	100
	Average	0.5	0.2	31.1	0.2	0.0	0.1	0.2	10.2	57.4	100
TzShihando7 RF7	Spectrum 1	0.8	0.4	30.5	0.1	0.1	0.1	0.1	9.8	58.0	100
	Spectrum 2	0.7	0.0	30.8	0.2	0.0	0.0	0.1	9.8	58.4	100
	Spectrum 3	0.7	0.1	30.8	0.2	0.1	0.0	0.2	9.6	58.3	100
	Average	0.7	0.2	30.7	0.1	0.1	0.1	0.1	9.7	58.2	100
TzShihando7 RF8	Spectrum 1	0.8	0.3	30.0	-0.1	0.1	0.1	0.3	14.0	54.6	100
	Spectrum 2	0.8	0.3	30.0	0.0	0.0	0.1	0.2	13.9	54.8	100
	Spectrum 3	0.3	0.3	30.2	0.0	0.1	0.1	0.2	13.0	55.8	100
	Average	0.6	0.3	30.0	0.0	0.0	0.1	0.2	13.6	55.1	100

Appendix 6.22: Full results of the EPMA composition of the iron droplets of the refining (RF) slags from Unyiha. Note the results are not normalised to 100 wt%

Sample	Si	P	Al	Cu	As	Mo	Ni	Co	Mn	Ti	C	Fe	AT
TzShihando7 RF5	0.00	0.01	0.01	0.02	0.00	0.04	0.00	0.00	0.19	0.02	4.73	97.49	102.51
TzShihando7 RF5	0.00	0.00	0.03	0.03	0.00	0.05	0.00	0.04	0.20	0.02	4.39	95.82	100.59
TzShihando7 RF5	0.00	0.04	0.01	0.05	0.00	0.07	0.04	0.00	0.09	0.01	0.92	95.97	97.19
TzShihando7 RF5	0.46	0.00	0.22	0.04	0.00	0.04	0.02	0.00	0.18	0.02	1.62	95.94	98.55
TzShihando7 RF5	0.00	0.14	0.01	0.03	0.00	0.08	0.00	0.00	0.10	0.01	1.02	97.27	98.67
TzShihando7 RF5	0.00	0.02	0.02	0.01	0.00	0.06	0.01	0.02	0.03	0.01	0.49	99.27	99.93

TzShihando7 RF5	0.00	0.01	0.02	0.03	0.00	0.02	0.01	0.00	0.09	0.01	4.06	95.97	100.21
Average	0.07	0.03	0.04	0.03	0.00	0.05	0.01	0.01	0.13	0.01	2.46	96.82	99.66
TzShihando7 RF6	0.00	0.01	0.02	0.03	0.00	0.03	0.00	0.00	0.03	0.00	1.10	96.45	97.67
TzShihando7 RF6	0.02	0.06	0.02	0.01	0.00	0.06	0.00	0.00	0.11	0.01	3.54	97.21	101.02
TzShihando7 RF6	0.00	0.01	0.02	0.05	0.00	0.17	0.10	0.19	0.11	0.02	1.95	94.85	97.46
TzShihando7 RF6	0.09	0.01	0.07	0.08	0.00	0.06	0.09	0.29	0.38	0.05	2.93	97.12	101.17
TzShihando7 RF6	0.00	0.00	0.04	0.06	0.00	0.63	0.28	0.67	0.25	0.02	3.10	94.29	99.33
TzShihando7 RF6	0.00	0.21	0.03	0.03	0.00	0.08	0.02	0.00	0.09	0.01	3.36	96.39	100.22
TzShihando7 RF6	0.00	0.01	0.02	0.03	0.00	0.05	0.03	0.06	0.06	0.00	3.45	97.58	101.28
											3.59	94.81	98.39
Average	0.01	0.04	0.03	0.04	0.00	0.15	0.07	0.17	0.15	0.02	2.78	96.27	99.74
TzShihando7 RF3	0.09	0.00	0.02	0.03	0.55	0.07	0.04	0.03	0.01	0.00	3.59	95.23	99.67
TzShihando7 RF3	0.10	0.00	0.02	0.03	0.49	0.08	0.05	0.04	0.01	0.00	0.86	96.18	97.83
TzShihando7 RF3	0.00	0.05	0.03	0.05	0.46	0.13	0.03	0.05	0.41	0.00	2.35	97.73	101.29
TzShihando7 RF3	0.00	0.01	0.03	0.04	0.00	0.14	0.07	0.11	0.13	0.01	1.21	96.76	98.49
TzShihando7 RF3	0.00	0.00	0.02	0.05	0.00	0.05	0.05	0.06	0.09	0.01	0.74	97.30	98.36
TzShihando7 RF3	0.00	0.00	0.01	0.04	0.00	0.04	0.06	0.09	0.07	0.00	2.04	97.19	99.53
TzShihando7 RF3	0.00	0.01	0.02	0.04	0.00	0.05	0.04	0.03	0.11	0.01	0.87	97.65	98.82
											2.04	95.92	97.96
											2.26	95.84	98.10
											2.78	96.55	99.33
Average	0.03	0.01	0.02	0.04	0.21	0.08	0.05	0.06	0.12	0.00	1.66	96.86	99.14
TzItaka2 RF3	0.09	0.01	0.02	0.04	0.52	0.01	0.02	0.06	0.07	0.00	1.09	97.64	99.57
TzItaka2 RF3	0.00	0.14	0.04	0.04	0.00	0.00	0.12	0.10	0.03	0.00	0.33	99.11	99.91
TzItaka2 RF3	0.08	0.01	0.08	0.01	0.55	0.01	0.11	0.14	0.13	0.00	1.35	98.68	101.16
TzItaka2 RF3	0.13	0.03	0.11	0.02	0.52	0.01	0.03	0.00	0.23	0.00	1.32	99.00	101.39
TzItaka2 RF3	0.01	0.23	0.02	0.04	0.00	0.07	0.09	0.14	0.15	0.06	0.22	97.04	98.06
TzItaka2 RF3	0.00	0.00	0.02	0.00	0.00	0.01	0.07	0.09	0.01	0.02		91.06	91.28
Average	0.05	0.07	0.05	0.02	0.27	0.02	0.07	0.09	0.10	0.01	0.86	97.70	99.32
TzItaka2 RF4	0.00	0.01	0.00	0.02	0.00	0.01	0.00	0.06	0.04	0.00	2.47	95.96	98.56
TzItaka2 RF4	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.06	0.05	0.00	2.32	97.16	99.63
TzItaka2 RF4	0.00	0.01	0.00	0.01	0.00	0.02	0.01	0.08	0.02	0.00	3.01	95.50	98.65
TzItaka2 RF4	0.00	0.00	0.00	0.02	0.00	0.00	0.02	0.09	0.03	0.00	2.55	96.74	99.45
TzItaka2 RF4	0.90	0.01	0.43	0.01	0.00	0.00	0.00	0.08	0.28	0.00	4.14	94.62	100.46
TzItaka2 RF4	0.06	0.00	0.08	0.00	0.00	0.00	0.02	0.14	0.14	0.00	3.83	97.36	101.63
TzItaka2 RF4	1.53	0.00	0.64	0.01	0.00	0.00	0.00	0.02	0.46	0.00	3.15	92.80	98.61
TzItaka2 RF4	0.00	0.01	0.00	0.02	0.00	0.00	0.01	0.08	0.04	0.00	4.36	95.57	100.08
											5.55	93.93	99.47
											3.10	97.24	100.34
Average	0.31	0.01	0.14	0.01	0.00	0.01	0.01	0.08	0.13	0.00	3.23	95.71	99.63
TzItaka2 RF6	0.49	0.05	0.18	0.01	0.00	0.00	0.01	0.06	0.14	0.00	3.65	95.27	99.85
TzItaka2 RF6	0.00	0.01	0.00	0.03	0.00	0.00	0.01	0.04	0.00	0.00	3.90	95.35	99.34
TzItaka2 RF6	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.06	0.01	0.00	1.77	96.83	98.69
TzItaka2 RF6	0.02	0.00	0.04	0.01	0.00	0.04	0.03	0.17	0.06	0.00	0.20	97.11	97.67
TzItaka2 RF6	0.00	0.02	0.00	0.02	0.00	0.05	0.03	0.15	0.09	0.00	4.06	96.12	100.55
TzItaka2 RF6	0.00	0.01	0.00	0.03	0.00	0.03	0.01	0.12	0.10	0.00	1.34	97.34	98.96
TzItaka2 RF6	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.06	0.04	0.00	2.59	96.62	99.32
TzItaka2 RF6	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.07	0.00	3.80	95.38	99.35
											4.30	96.11	100.41
											4.30	95.23	99.53
Average	0.06	0.01	0.03	0.02	0.00	0.02	0.01	0.09	0.06	0.00	2.66	96.25	99.22

Appendix 7: Chapter 7 Appendices

Appendix 7.1: List of smelting sites and smithing site from Mkulusi village Note that SE stands for smelting, ST for smithing site, and DWS for distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (10^0 45.649'), E (35^0 4.045')	61	452	1034	Philoteus Komba
2	SE2	S (10^0 46.538'), E (35^0 4.566')	50	113	1115	Philoteus Komba
3	SE3	S (10^0 46.504'), E (35^0 4.848')	5	227	1132	Philoteus Komba
4	ST4	S (10^0 46.297'), E (35^0 4.643')	178	48	1108	Philoteus Komba
5	SE5	S (10^0 46.517'), E (35^0 6.350')	40	186	963	Frank Sewando
6	SE6	S (10^0 45.387'), E (35^0 4.321')	60	266	985	Andason Mbawala
7	SE7	S (10^0 45.345'), E (35^0 4.307')	61	154	1017	Philoteus Komba
8	SE8	S (10^0 45.376'), E (35^0 4.253')	31	314	1027	Philoteus Komba
9	SE9	S (10^0 45.468'), E (35^0 4.050')	250	79	1092	Edwinus Lyaya
10	SE10	S (10^0 45.450'), E (35^0 4.060')	341	80	1030	Edwinus Lyaya
11	SE11	S (10^0 45.371'), E (35^0 4.258')	44	56	1022	Edwinus Lyaya
12	SE12	S (10^0 45.355'), E (35^0 4.310')	36	49	1012	Edwinus Lyaya
13	SE13	S (10^0 46.357'), E (35^0 4.573')	13	50	1119	Philoteus Komba
14	SE14	S (10^0 46.354'), E (35^0 4.573')	11	108	1117	Philoteus Komba
15	**Mean**		**84**	**156**	**1055**	

Appendix 7.2: List of smelting sites from Kihuluku village Note that SE stands for smelting, and DWS for distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (10^0 43.927'), E (35^0 4.741')	20	113	1014	Philoteus Komba
2	SE2	S (10^0 43.952'), E (35^0 4.771')	30	117	1009	Philoteus Komba
3	SE3	S (10^0 44.008'), E (35^0 4.790')	20	177	992	Philoteus Komba
4	SE4	S (10^0 44.030'), E (35^0 4.766')	20	430	983	Edwinus Lyaya
5	**Mean**		**23**	**209**	**1000**	

Appendix 7.3: List of smelting sites and pottery site from Matalawe and Halale villages. Note that SE stands for smelting, PS for pottery site, HA for Halale, and DWS for distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (10^0 48' 17.4"), E (35^0 5' 59.3"	130	61	1047	Watford Milinga
2	SE2	S (10^0 48' 53.4"), E (35^0 6' 22.4"	150	34	1146	Watford Milinga
3	SE3	S (10^0 48' 38.5"), E (35^0 6' 12.8"	120	109	1104	Watford Milinga
4	ST4	S (10^0 48' 39.6"), E (35^0 6' 12.6"	68	113	1099	Salum Muya
5	SE5	S (10^0 48' 11.7"), E (35^0 6' 7.9"	78	254	1092	Adolf Kapinga
6	SE6	S (10^0 48' 19.6"), E (35^0 6' 28"	110	154	1061	Amos Njelekela
7	SE7	S (10^0 48' 27"), E (35^0 6' 22.5"	139	82	1092	Amos Njelekela
8	PS8	S (10^0 48' 10.4"), E (35^0 6' 0.5"	100	79	1090	Salum Muya
9	HASE1	S (10^0 47.751'), E (35^0 5.134'	180	201	1029	Galus Mholo
10	**Mean**		**119**	**121**	**1084**	

Appendix 7.4: List of smelting sites and pottery site from Minazi village. Note that SE stands for smelting, PS for pottery site, and DWS for distance to the nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	SE1	S (10^0 47.016'), E (35^0 3.135')	20	359	1115	Barnabas Kawonga
2	SE2	S (10^0 46.453'), E (35^0 3.372')	100	232	1094	Elias Nyika
3	SE3	S (10^0 46.357'), E (35^0 3.282')	100	201	1101	Cleophas Ndomba
4	PS4	S (10^0 46.112'), E (35^0 3.657')	90	3	1084	Edwinus Lyaya
5	**Mean**		**78**	**199**	**1098**	

Appendix 7.5: Scanned image of multiple tuyère illustration from western Matengo by Kapinga 1990: 16

Appendix 7.6: Full results of the (P) XRF-EDS major and minor element concentrations of the technical ceramics from Ntuha site. Note the results are not normalised to 100 wt%, FW=furnace wall, PLT=platform, TYR=tuyère, and PTR=pottery

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzNtuha1 FW1	1.19	1.77	19.89	74.11	0.08	0.01	1.57	1.39	0.70	0.00	0.02	0.13	2.06	103
TzNtuha1 FW1_r01	1.02	1.71	19.99	74.19	0.07	0.01	1.56	1.41	0.71	0.01	0.02	0.13	2.07	103
TzNtuha1 FW1_r02	1.28	1.75	19.92	74.01	0.05	0.02	1.58	1.40	0.71	0.00	0.02	0.12	2.05	103
Average	1.16	1.74	19.93	74.10	0.07	0.01	1.57	1.40	0.71	0.00	0.02	0.12	2.06	103
TzNtuha2 FW2	1.24	1.67	18.83	75.36	0.05	0.01	1.54	1.59	0.65	0.00	0.01	0.12	1.81	103
TzNtuha2 FW2_r01	1.23	1.63	18.94	75.24	0.07	0.01	1.57	1.59	0.67	0.00	0.01	0.12	1.81	103
TzNtuha2 FW2_r02	1.26	1.60	18.87	75.33	0.07	0.01	1.57	1.58	0.65	0.00	0.01	0.12	1.82	103
Average	1.24	1.63	18.88	75.31	0.06	0.01	1.56	1.58	0.66	0.00	0.01	0.12	1.82	103
TzNtuhaS FW3	0.96	0.81	21.95	74.67	0.08	0.04	1.64	0.16	0.62	0.00	0.02	0.05	1.91	103
TzNtuhaS FW3_r01	1.23	0.90	22.00	74.33	0.10	0.04	1.59	0.15	0.61	0.00	0.02	0.05	1.88	103
TzNtuhaS FW3_r02	1.20	0.82	21.95	74.45	0.10	0.04	1.60	0.16	0.62	0.00	0.02	0.05	1.90	103
Average	1.13	0.84	21.97	74.48	0.10	0.04	1.61	0.16	0.62	0.00	0.02	0.05	1.90	103
TzNtuha2 PTR1	3.92	4.26	26.62	56.03	0.59	0.00	0.82	3.51	0.96	0.03	0.02	0.09	6.05	103
TzNtuha2 PTR1_r01	4.44	4.12	26.69	55.73	0.57	0.00	0.80	3.46	0.96	0.02	0.02	0.09	5.99	103
TzNtuha2 PTR1_r02	4.59	4.10	26.64	55.60	0.58	0.00	0.82	3.47	0.97	0.02	0.02	0.09	6.02	103
Average	4.32	4.16	26.65	55.79	0.58	0.00	0.81	3.48	0.96	0.02	0.02	0.09	6.02	103
TzNtuha1 PTR2	4.66	4.17	26.02	56.75	0.42	0.00	0.83	3.36	0.89	0.02	0.02	0.07	5.70	103
TzNtuha1 PTR2_r01	4.56	4.15	26.15	56.82	0.42	0.00	0.80	3.34	0.88	0.02	0.02	0.07	5.66	103
TzNtuha1 PTR2_r02	4.23	4.37	26.29	56.76	0.42	0.00	0.82	3.33	0.89	0.02	0.02	0.08	5.68	103
Average	4.48	4.23	26.15	56.78	0.42	0.00	0.82	3.34	0.89	0.02	0.02	0.07	5.68	103
TzNtuha2 PTR3	3.54	3.50	26.77	57.04	0.58	0.00	1.80	2.98	0.87	0.02	0.01	0.07	5.67	103
TzNtuha2 PTR3_r01	3.33	3.69	26.94	56.98	0.57	0.00	1.79	2.96	0.86	0.02	0.01	0.07	5.63	103
TzNtuha2 PTR3_r02	3.58	3.71	26.87	56.78	0.59	0.00	1.76	2.97	0.87	0.02	0.01	0.07	5.63	103
Average	3.48	3.63	26.86	56.93	0.58	0.00	1.78	2.97	0.87	0.02	0.01	0.07	5.65	103
TzNtuha1 TYR1	1.13	0.91	16.16	79.22	0.08	0.01	1.43	1.27	0.56	0.00	0.02	0.12	2.00	103
TzNtuha1 TYR1_r01	1.34	0.94	16.15	79.04	0.08	0.01	1.42	1.25	0.55	0.00	0.02	0.12	1.99	103
TzNtuha1 TYR1_r02	1.47	0.96	16.12	78.97	0.08	0.01	1.42	1.25	0.54	0.00	0.02	0.12	1.98	103
Average	1.31	0.94	16.14	79.08	0.08	0.01	1.42	1.26	0.55	0.00	0.02	0.12	1.99	103
TzNtuha2 TYR2	1.40	1.09	21.75	74.65	0.05	0.02	1.28	0.36	0.57	0.00	0.01	0.06	1.68	103
TzNtuha2 TYR2_r01	1.69	1.05	21.74	74.45	0.03	0.02	1.27	0.36	0.55	0.01	0.01	0.06	1.67	103

TzNtuha2 TYR2_r02	1.41	1.08	21.69	74.71	0.04	0.02	1.27	0.37	0.58	0.00	0.01	0.06	1.68	103
Average	1.50	1.08	21.73	74.60	0.04	0.02	1.27	0.37	0.57	0.00	0.01	0.06	1.68	103
TzNtuha3 TYR3	1.22	0.81	21.92	75.10	0.08	0.03	1.21	0.35	0.56	0.00	0.01	0.07	1.57	103
TzNtuha3 TYR3_r01	1.08	0.82	21.96	75.18	0.05	0.03	1.22	0.36	0.57	0.00	0.01	0.06	1.57	103
TzNtuha3 TYR3_r02	1.36	0.82	21.93	74.93	0.08	0.03	1.22	0.35	0.56	0.00	0.01	0.07	1.56	103
Average	1.22	0.81	21.94	75.07	0.07	0.03	1.21	0.35	0.56	0.00	0.01	0.07	1.57	103
TzNtuhaS PLT1	0.93	0.45	21.97	75.34	0.05	0.03	1.48	0.11	0.64	0.00	0.01	0.05	1.84	103
TzNtuhaS PLT1_r01	0.76	0.56	21.85	75.48	0.07	0.03	1.50	0.11	0.64	0.00	0.01	0.05	1.84	103
TzNtuhaS PLT1_r02	1.20	0.47	21.83	75.17	0.07	0.04	1.49	0.11	0.64	0.00	0.01	0.05	1.83	103
Average	0.96	0.49	21.88	75.33	0.06	0.03	1.49	0.11	0.64	0.00	0.01	0.05	1.83	103
TzNtuhaS PLT2	1.01	0.51	20.25	77.10	0.04	0.03	1.41	0.15	0.59	0.00	0.02	0.05	1.74	103
TzNtuhaS PLT2_r01	0.93	0.54	20.18	77.15	0.06	0.03	1.42	0.15	0.59	0.00	0.02	0.05	1.76	103
TzNtuhaS PLT2_r02	0.91	0.55	20.16	77.20	0.07	0.04	1.42	0.14	0.58	0.00	0.02	0.05	1.75	103
Average	0.95	0.53	20.20	77.15	0.06	0.03	1.42	0.15	0.59	0.00	0.02	0.05	1.75	103
TzNtuhaS PLT3	0.87	0.54	20.49	76.91	0.04	0.04	1.44	0.11	0.60	0.00	0.02	0.05	1.79	103
TzNtuhaS PLT3_r01	1.05	0.51	20.43	76.81	0.07	0.04	1.43	0.11	0.60	0.00	0.02	0.05	1.78	103
TzNtuhaS PLT3_r02	1.54	0.53	20.44	76.34	0.07	0.04	1.41	0.11	0.58	0.00	0.02	0.05	1.76	103
Average	1.15	0.53	20.45	76.69	0.06	0.04	1.43	0.11	0.59	0.00	0.02	0.05	1.78	103

Appendix 7.7: Full results of the (P) XRF-EDS trace element concentrations of the technical ceramics from Ntuha site. Note the results are not normalised to 100 wt%, FW=furnace wall, PLT=platform, TYR=tuyère, and PTR=pottery

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	SnO2	Ba	La	Ce
TzNtuha1 FW1	42	16	47	30	8	53	74	22	223	3	268	10	29
TzNtuha1 FW1_r01	40	12	48	29	7	54	76	22	236	3	273	12	31
TzNtuha1 FW1_r02	36	15	46	31	7	53	74	21	230	3	272	10	31
Average	39	14	47	30	7	53	75	22	229	3	271	10	30
TzNtuha2 FW2	48	13	145	29	6	50	82	21	250	11	389	9	30
TzNtuha2 FW2_r01	35	12	143	30	5	49	82	22	243	11	383	11	30
TzNtuha2 FW2_r02	30	12	147	26	7	50	82	22	242	11	385	8	30
Average	37	12	145	28	6	49	82	21	245	11	386	10	30
TzNtuhaS FW3	28	10	122	28	6	42	30	19	195	9	315	6	23
TzNtuhaS FW3_r01	36	11	119	27	7	42	30	18	196	9	313	8	25
TzNtuhaS FW3_r02	30	15	121	26	7	43	30	18	188	10	308	7	16
Average	31	12	121	27	7	42	30	18	193	9	312	7	21
TzNtuha2 PTR1	122	52	22	66	15	17	300	15	55	1	256	9	19
TzNtuha2 PTR1_r01	135	54	23	66	14	16	295	15	53	1	257	10	14
TzNtuha2 PTR1_r02	123	53	21	69	14	17	296	14	54	1	248	8	14
Average	127	53	22	67	14	17	297	14	54	1	254	9	16
TzNtuha1 PTR2	81	48	82	61	14	16	273	14	55	6	275	11	10
TzNtuha1 PTR2_r01	61	54	81	63	14	17	270	14	57	6	274	11	12
TzNtuha1 PTR2_r02	55	57	80	67	14	17	272	14	58	6	278	10	10
Average	66	53	81	64	14	17	272	14	57	6	276	11	11
TzNtuha2 PTR3	57	31	81	58	14	41	423	11	84	2	495	7	14
TzNtuha2 PTR3_r01	64	28	87	54	15	42	421	11	79	2	488	8	23
TzNtuha2 PTR3_r02	62	27	87	54	15	42	423	11	87	3	491	10	14
Average	61	29	85	56	15	42	422	11	84	3	491	8	17
TzNtuha1 TYR1	37	13	101	24	8	47	67	19	247	9	185	13	19
TzNtuha1 TYR1_r01	38	8	98	26	9	46	67	19	237	8	181	14	30
TzNtuha1 TYR1_r02	37	8	99	23	7	46	66	19	241	8	179	11	28
Average	37	10	99	24	8	46	67	19	242	8	182	13	26
TzNtuha2 TYR2	35	16	71	23	7	37	31	17	242	6	142	12	23
TzNtuha2 TYR2_r01	35	17	74	21	8	37	31	17	244	6	137	11	29
TzNtuha2 TYR2_r02	31	15	77	22	7	37	31	17	251	6	141	12	24
Average	34	16	74	22	7	37	31	17	246	6	140	11	25
TzNtuha3 TYR3	23	13	85	23	7	34	32	18	254	7	159	14	29
TzNtuha3 TYR3_r01	24	14	82	25	7	34	32	18	245	7	159	11	27
TzNtuha3 TYR3_r02	37	9	84	23	7	34	31	18	248	7	161	14	30
Average	28	12	84	24	7	34	32	18	249	7	159	13	29
TzNtuhaS PLT1	33	11	225	23	7	38	26	18	209	17	339	11	25
TzNtuhaS PLT1_r01	32	12	222	24	5	38	26	18	209	17	334	8	14
TzNtuhaS PLT1_r02	30	10	227	25	6	39	26	18	204	17	335	9	24
Average	32	11	225	24	6	38	26	18	207	17	336	9	21
TzNtuhaS PLT2	35	11	170	25	7	40	36	18	188	12	450	6	20
TzNtuhaS PLT2_r01	30	11	166	24	6	40	37	17	183	12	449	6	24
TzNtuhaS PLT2_r02	38	12	166	24	6	39	36	17	194	13	443	8	22
Average	34	11	168	24	6	39	36	17	188	12	447	7	22
TzNtuhaS PLT3	33	12	182	24	6	39	28	19	215	14	370	8	16
TzNtuhaS PLT3_r01	40	12	183	22	7	39	27	18	208	14	362	6	24

TzNtuhaS PLT3_r02	39	11	182	23	7	38	27	19	199	14	359	7	17
Average	37	12	183	23	7	39	27	19	207	14	364	7	19

Appendix 7.8: Full results of the (P) XRF-EDS major and minor oxide compositions of the technical ceramics from Mkulusi #1 site. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMkulusi1 FW1	0.45	0.61	31.06	58.69	0.21	0.03	1.47	0.36	1.72	0.03	0.03	0.16	8.08	103
TzMkulusi1 FW1_r01	0.32	0.57	31.17	58.67	0.21	0.03	1.51	0.36	1.73	0.03	0.03	0.16	8.11	103
Average	0.39	0.59	31.12	58.68	0.21	0.03	1.49	0.36	1.72	0.03	0.03	0.16	8.10	103
TzMkulusi1 FW2	0.47	0.78	30.08	59.96	0.19	0.02	1.34	0.51	1.73	0.03	0.02	0.14	7.61	103
TzMkulusi1 FW2_r01	0.34	0.72	30.05	60.16	0.20	0.02	1.31	0.54	1.74	0.03	0.03	0.14	7.62	103
Average	0.41	0.75	30.07	60.06	0.19	0.02	1.33	0.53	1.74	0.03	0.03	0.14	7.61	103
TzMkulusi1 FW3	0.55	0.54	32.64	57.60	0.17	0.02	1.44	0.35	1.69	0.03	0.02	0.13	7.73	103
TzMkulusi1 FW3_r01	0.47	0.59	32.71	57.56	0.17	0.03	1.46	0.35	1.66	0.03	0.02	0.13	7.74	103
Average	0.51	0.56	32.68	57.58	0.17	0.02	1.45	0.35	1.67	0.03	0.02	0.13	7.73	103
TzMkulusi1 TYR1	1.29	0.63	24.38	69.81	0.13	0.02	1.84	0.24	2.27	0.03	0.02	0.04	2.18	103
TzMkulusi1 TYR1_r01	1.28	0.56	24.40	69.85	0.13	0.03	1.83	0.24	2.27	0.02	0.02	0.04	2.19	103
TzMkulusi1 TYR1_r02	1.13	0.60	24.34	70.04	0.13	0.03	1.82	0.25	2.26	0.02	0.02	0.04	2.19	103
Average	1.23	0.60	24.37	69.90	0.13	0.03	1.83	0.24	2.27	0.02	0.02	0.04	2.19	103
TzMkulusi1 TYR2	0.84	0.78	27.73	68.47	0.09	0.02	2.38	0.17	0.84	0.02	0.02	0.02	1.52	103
TzMkulusi1 TYR2_r01	0.92	0.74	27.80	68.42	0.09	0.02	2.35	0.17	0.82	0.02	0.02	0.02	1.51	103
Average	0.88	0.76	27.77	68.45	0.09	0.02	2.37	0.17	0.83	0.02	0.02	0.02	1.52	103
TzMkulusi1 TYR3	0.92	0.63	25.97	69.02	0.15	0.02	0.86	0.26	1.37	0.03	0.02	0.03	3.67	103
TzMkulusi1 TYR3_r01	0.72	0.62	26.05	69.13	0.16	0.03	0.86	0.26	1.37	0.03	0.02	0.03	3.67	103
Average	0.82	0.62	26.01	69.08	0.15	0.03	0.86	0.26	1.37	0.03	0.02	0.03	3.67	103
TzMkulusi1 PTR1	2.52	0.62	40.91	51.50	0.25	0.00	0.57	4.27	0.37	0.00	0.00	0.02	1.91	103
TzMkulusi1 PTR1_r01	2.54	0.59	40.98	51.44	0.25	0.00	0.56	4.27	0.37	0.00	0.00	0.02	1.92	103
Average	2.53	0.60	40.95	51.47	0.25	0.00	0.56	4.27	0.37	0.00	0.00	0.02	1.92	103
TzMkulusi1 PTR2	3.58	0.77	37.69	52.62	0.25	0.00	0.48	5.12	0.38	0.00	0.01	0.02	2.01	103
TzMkulusi1 PTR2_r01	3.93	0.76	37.58	52.45	0.25	0.00	0.48	5.08	0.39	0.01	0.01	0.02	2.00	103
Average	3.76	0.77	37.64	52.54	0.25	0.00	0.48	5.10	0.38	0.00	0.01	0.02	2.00	103
TzMkulusi1 PTR3	3.32	0.85	38.25	52.10	0.29	0.00	0.52	5.12	0.39	0.00	0.00	0.02	2.05	103
TzMkulusi1 PTR3_r01	2.96	0.85	38.32	52.31	0.30	0.00	0.51	5.19	0.40	0.00	0.00	0.02	2.07	103
Average	3.14	0.85	38.29	52.21	0.30	0.00	0.52	5.16	0.39	0.00	0.00	0.02	2.06	103

Appendix 7.9: Full results of the (P) XRF-EDS trace oxide compositions of the technical ceramics from Mkulusi #1 site. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	SnO2	Ba	La	Ce	Hf	Ta2O5	WO3	PbO	Th
TzMkulusi1 FW1	99	44	115	253	16	56	24	34	179	11	7	108	22	42	7	8	35	63	11
TzMkulusi1 FW1_r01	115	42	112	248	15	55	25	35	184	11	8	110	25	43	8	9	41	66	12
Average	107	43	113	251	15	55	24	34	181	11	7	109	24	42	7	8	38	64	11
TzMkulusi1 FW2	115	33	98	66	15	48	30	33	174	11	4	111	22	41	7	8	45	57	12
TzMkulusi1 FW2_r01	125	30	98	68	16	48	30	34	185	13	4	109	19	38	7	9	41	55	13
Average	120	32	98	67	16	48	30	34	179	12	4	110	20	40	7	9	43	56	12
TzMkulusi1 FW3	134	36	89	60	16	56	27	34	188	11	5	105	23	41	6	14	7	17	13
TzMkulusi1 FW3_r01	123	38	86	61	14	56	25	35	189	12	3	105	20	37	9	15	6	18	11
Average	129	37	87	61	15	56	26	34	189	11	4	105	22	39	8	14	6	18	12
TzMkulusi1 TYR1	45	29	137	41	12	39	27	32	504	12	10	139	33	62	22	9	152	19	32
TzMkulusi1 TYR1_r01	55	27	134	40	10	39	26	32	510	13	11	139	30	63	21	9	146	20	33
TzMkulusi1 TYR1_r02	58	26	137	41	11	40	26	31	487	12	11	139	31	66	23	9	142	19	31
Average	53	27	136	41	11	39	26	32	500	12	11	139	31	64	22	9	146	19	32
TzMkulusi1 TYR2	29	30	161	35	12	71	31	25	121	5	11	207	22	61	8	10	148	29	27
TzMkulusi1 TYR2_r01	33	26	164	34	13	71	31	25	119	5	12	208	22	65	8	10	139	29	26
Average	31	28	163	35	12	71	31	25	120	5	12	208	22	63	8	10	144	29	26
TzMkulusi1 TYR3	60	37	57	44	13	29	17	21	156	9	2	78	13	32	7	6	55	17	15
TzMkulusi1 TYR3_r01	60	39	59	41	12	30	17	21	154	9	2	76	11	28	6	5	56	18	15
Average	60	38	58	42	12	29	17	21	155	9	2	77	12	30	6	6	56	17	15
TzMkulusi1 PTR1	25	11	28	17	13	12	301	6	27	2	1	140	6	8	4	3	27	6	3
TzMkulusi1 PTR1_r01	36	10	25	14	12	12	300	6	30	1	1	139	6	8	3	4	29	6	3
Average	30	10	26	16	13	12	301	6	28	2	1	139	6	8	4	4	28	6	3
TzMkulusi1 PTR2	39	10	19	18	13	8	334	5	25	2	1	132	6	8	3	4	66	4	2

TzMkulusi1 PTR2_r01	23	10	18	16	13	8	333	5	25	2	1	130	6	8	3	4	67	4	2
Average	31	10	18	17	13	8	333	5	25	2	1	131	6	8	3	4	66	4	2
TzMkulusi1 PTR3	27	9	11	17	13	8	356	4	25	3	1	147	6	9	3	3	54	4	2
TzMkulusi1 PTR3_r01	30	13	12	18	13	8	359	5	27	2	1	143	6	8	3	3	60	5	1
Average	28	11	11	18	13	8	358	4	26	3	1	145	6	9	3	3	57	5	2

Appendix 7.10: Full results of the (P) XRF-EDS major and minor oxide concentrations of the technical ceramics from Mkulusi #7 site. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMkulusi7 FW1	0.91	1.20	26.54	63.01	0.30	0.03	1.86	0.54	1.60	0.03	0.05	0.13	6.70	103
TzMkulusi7 FW1_r01	1.07	1.25	26.49	62.82	0.29	0.03	1.89	0.54	1.64	0.03	0.05	0.13	6.67	103
TzMkulusi7 FW1_r02	0.30	1.20	26.69	63.36	0.29	0.03	1.90	0.55	1.61	0.03	0.05	0.13	6.75	103
Average	0.76	1.22	26.57	63.06	0.29	0.03	1.88	0.54	1.62	0.03	0.05	0.13	6.71	103
TzMkulusi7 FW2	0.95	0.51	21.02	71.18	0.57	0.03	1.19	0.21	1.54	0.02	0.02	0.06	5.62	103
TzMkulusi7 FW2_r01	0.77	0.46	20.99	71.39	0.57	0.04	1.20	0.19	1.55	0.03	0.02	0.06	5.66	103
TzMkulusi7 FW2_r02	0.96	0.59	21.07	71.02	0.56	0.04	1.20	0.20	1.54	0.03	0.02	0.06	5.62	103
Average	0.89	0.52	21.03	71.20	0.57	0.04	1.20	0.20	1.54	0.03	0.02	0.06	5.63	103
TzMkulusi7 FW3	1.26	0.55	18.62	73.41	0.28	0.02	1.15	0.20	1.38	0.03	0.03	0.07	5.94	103
TzMkulusi7 FW3_r01	1.20	0.50	18.55	73.59	0.26	0.02	1.12	0.19	1.40	0.02	0.03	0.07	5.97	103
TzMkulusi7 FW3_r02	1.07	0.53	18.59	73.67	0.27	0.02	1.12	0.19	1.37	0.03	0.03	0.07	5.97	103
Average	1.18	0.52	18.59	73.56	0.27	0.02	1.13	0.19	1.38	0.03	0.03	0.07	5.96	103
TzMkulusi7 TYR1	0.66	1.34	29.34	65.88	0.30	0.02	2.84	0.30	0.62	0.01	0.01	0.02	1.58	103
TzMkulusi7 TYR1_r01	0.99	1.32	29.26	65.71	0.29	0.02	2.84	0.28	0.60	0.01	0.01	0.02	1.56	103
Average	0.83	1.33	29.30	65.80	0.29	0.02	2.84	0.29	0.61	0.01	0.01	0.02	1.57	103
TzMkulusi7 TYR2	0.84	0.85	30.55	64.98	0.30	0.02	2.62	0.29	0.81	0.02	0.02	0.02	1.60	103

TzMkulusi7 TYR2_r01	0.55	0.90	30.62	65.08	0.31	0.02	2.65	0.28	0.83	0.01	0.02	0.02	1.62	103
Average	0.70	0.88	30.59	65.03	0.30	0.02	2.63	0.29	0.82	0.01	0.02	0.02	1.61	103
TzMkulusi7 TYR3	0.83	0.81	28.69	67.62	0.28	0.02	2.31	0.19	0.80	0.02	0.02	0.02	1.32	103
TzMkulusi7 TYR3_r01	0.99	0.91	28.58	67.48	0.28	0.03	2.32	0.17	0.81	0.02	0.02	0.02	1.32	103
Average	0.91	0.86	28.64	67.55	0.28	0.03	2.31	0.18	0.80	0.02	0.02	0.02	1.32	103
TzMkulusi7 PTR1	4.00	1.01	33.80	55.65	0.66	0.00	0.99	4.78	0.32	0.01	0.01	0.02	1.68	103
TzMkulusi7 PTR1_r01	4.25	1.07	33.76	55.44	0.67	0.00	0.96	4.76	0.32	0.01	0.01	0.02	1.67	103
TzMkulusi7 PTR1_r02	4.20	0.91	33.78	55.56	0.68	0.00	0.97	4.78	0.32	0.01	0.01	0.02	1.69	103
Average	4.23	0.99	33.77	55.50	0.67	0.00	0.97	4.77	0.32	0.01	0.01	0.02	1.68	103
TzMkulusi7 PTR2	3.09	1.00	36.17	53.18	0.32	0.00	0.55	4.19	0.76	0.02	0.01	0.02	3.61	103
TzMkulusi7 PTR2_r01	2.56	0.99	36.32	53.49	0.32	0.00	0.54	4.22	0.77	0.02	0.01	0.02	3.66	103
TzMkulusi7 PTR2_r02	2.92	1.00	36.25	53.24	0.32	0.00	0.54	4.19	0.77	0.02	0.01	0.02	3.64	103
Average	2.86	1.00	36.25	53.30	0.32	0.00	0.55	4.20	0.77	0.02	0.01	0.02	3.64	103
TzMkulusi7 PTR3	2.96	0.63	38.58	52.72	0.38	0.00	0.83	4.58	0.37	0.00	0.01	0.02	1.85	103
TzMkulusi7 PTR3_r01	2.55	0.69	38.81	52.84	0.38	0.00	0.84	4.58	0.36	0.01	0.01	0.02	1.85	103
TzMkulusi7 PTR3_r02	2.85	0.65	38.72	52.68	0.38	0.00	0.82	4.57	0.37	0.01	0.01	0.02	1.85	103
Average	2.79	0.66	38.70	52.75	0.38	0.00	0.83	4.57	0.37	0.01	0.01	0.02	1.85	103

Appendix 7.11: Full results of the (P) XRF-EDS trace oxide concentrations of the technical ceramics from Mkulusi #7 site. Note the results are not normalised to 100 wt%, FW=furnace wall, TYR=tuyère, and PTR=pottery

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	SnO2	Ba	La	Ce	Hf	Ta2O5	WO3	PbO	Th
TzMkulusi7 FW1	134	47	64	62	15	71	37	39	186	13	2	188	18	39	6	7	63	22	13
TzMkulusi7 FW1_r01	122	51	57	62	13	72	36	39	180	13	2	186	19	43	9	16	62	21	15
TzMkulusi7 FW1_r02	117	51	61	62	15	72	36	39	189	11	3	189	22	43	10	11	58	23	13
Average	124	50	61	62	14	71	36	39	185	12	2	188	20	42	8	11	61	22	14
TzMkulusi7 FW2	59	33	98	44	11	40	20	28	187	10	7	114	22	36	7	8	101	16	14

TzMkulusi7 FW2_r01	71	34	95	46	11	41	20	28	190	12	6	114	21	40	11	8	98	16	15
TzMkulusi7 FW2_r02	54	37	97	44	11	39	20	28	188	12	7	115	21	39	9	8	98	16	14
Average	61	35	97	44	11	40	20	28	189	11	7	115	21	38	9	8	99	16	14
TzMkulusi7 FW3	70	34	46	45	10	40	16	26	166	11	1	102	19	32	9	6	75	8	13
TzMkulusi7 FW3_r01	68	30	41	46	9	40	16	26	166	11	2	98	20	37	7	11	71	8	12
TzMkulusi7 FW3_r02	61	32	40	48	9	41	16	27	163	11	1	101	17	34	9	8	71	8	13
Average	66	32	43	46	9	40	16	26	165	11	2	100	19	35	8	8	72	8	12
TzMkulusi7 TYR1	42	17	26	26	11	74	35	22	116	5	1	217	14	39	8	6	82	22	16
TzMkulusi7 TYR1_r01	37	21	27	28	10	75	35	22	110	5	2	214	14	34	10	7	90	21	14
Average	40	19	26	27	11	74	35	22	113	5	2	215	14	36	9	6	86	22	15
TzMkulusi7 TYR2	39	30	42	33	11	74	41	23	134	5	2	241	14	43	7	5	75	26	17
TzMkulusi7 TYR2_r01	38	27	42	32	13	75	41	24	138	6	2	243	13	42	10	6	71	26	18
Average	38	28	42	33	12	74	41	23	136	5	2	242	14	43	9	5	73	26	18
TzMkulusi7 TYR3	23	17	18	26	11	62	31	25	153	7	1	209	20	61	9	6	48	26	25
TzMkulusi7 TYR3_r01	29	20	21	25	11	61	30	25	144	7	1	209	21	58	8	4	51	27	24
Average	26	18	20	26	11	61	30	25	149	7	1	209	21	60	8	5	50	27	25
TzMkulusi7 PTR1	37	4	10	15	11	22	377	4	33	3	1	131	6	8	3	3	20	5	3
TzMkulusi7 PTR1_r01	21	7	7	16	10	21	375	4	28	2	1	128	6	8	5	6	23	6	3
TzMkulusi7 PTR1_r02	19	8	9	17	11	22	379	4	27	2	1	129	6	8	3	4	23	4	3
Average	20	8	8	17	10	22	377	4	27	2	1	128	6	8	4	5	23	5	3
TzMkulusi7 PTR2	44	14	21	27	13	13	356	3	19	3	1	89	6	8	3	4	79	5	1
TzMkulusi7 PTR2_r01	41	18	24	27	13	13	361	4	21	2	1	88	5	8	4	4	91	6	2
TzMkulusi7 PTR2_r02	51	13	20	26	13	13	359	4	21	2	1	88	5	8	3	5	75	6	2
Average	45	15	22	27	13	13	359	4	20	2	1	88	6	8	3	5	82	6	2
TzMkulusi7 PTR3	22	15	19	14	14	20	400	4	10	2	1	142	6	8	3	5	26	5	3
TzMkulusi7 PTR3_r01	39	15	19	11	15	20	404	4	10	2	1	139	6	8	3	4	23	5	3
TzMkulusi7 PTR3_r02	28	12	17	13	14	20	400	4	9	2	1	143	7	8	3	6	25	5	3
Average	30	14	18	12	14	20	401	4	10	2	1	141	6	8	3	5	25	5	3

Appendix 7.12: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) slags from Ntuha, Mkulusi 1 and 7 sites. The results are the average of three areas measured at *x*200 and are normalised to 100 wt%

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO2	K2O	CaO	TiO2	MnO	FeO	BaO	Total
TzNtuha2 SE1	0.3	0.6	9.8	26.8	0.4	0.2	1.8	3.8	0.3	3.7	52.3	0.3	100.3
TzNtuha2 SE2	0.2	0.4	5.4	10.1	0.1	0.0	0.5	1.5	0.2	3.5	78.7	0.0	100.5
TzNtuha2 SE3	0.0	0.7	3.1	9.1	0.1	0.1	0.5	0.5	0.0	2.9	83.5	0.1	100.5
TzNtuha1 SE4	0.2	0.8	6.9	23.3	0.3	0.2	0.9	1.1	0.2	3.6	62.7	0.2	100.5
TzNtuhaS SE5	0.3	0.6	6.2	28.0	0.2	0.0	1.0	0.9	0.2	3.6	59.0	0.1	100.2
TzMkulusi1 SE1	0.1	1.0	10.1	45.0	0.4	0.0	2.0	2.2	1.0	0.9	37.2	0.1	100.0
TzMkulusi1 SE2	0.1	0.6	7.9	43.8	0.5	0.0	1.4	2.4	1.1	0.1	42.0	0.2	100.0
TzMkulusi1 SE3	0.1	0.5	8.7	39.0	0.9	0.0	1.2	3.7	1.3	0.2	44.5	0.0	100.0
TzMkulusi1 SE4	0.0	0.5	7.9	42.0	0.5	0.1	1.3	2.2	1.2	0.1	44.1	0.0	100.0
TzMkulusi1 SE5	0.1	0.4	5.0	44.3	0.5	0.1	1.1	1.6	1.0	0.0	45.9	0.1	100.0
TzMkulusi7 SE1	0.0	0.8	8.3	41.8	0.5	0.0	1.2	4.7	1.1	0.2	42.3	-0.1	100.8
TzMkulusi7 SE2	0.1	0.9	7.6	40.5	0.9	-0.1	1.6	2.8	1.0	0.0	44.7	0.0	99.9
TzMkulusi7 SE3	0.0	0.5	7.6	40.7	0.6	0.0	1.3	1.7	1.1	0.0	46.7	0.0	100.1
TzMkulusi7 SE4	0.0	1.0	7.3	40.5	1.0	-0.1	1.7	3.2	1.1	0.1	44.4	0.1	100.3
TzMkulusi7 SE5	0.1	1.1	7.8	40.7	1.2	0.1	1.9	3.6	1.0	0.1	42.6	0.1	100.4

Appendix 7.13: Full results of the SEM-EDS bulk area composition of the major and minor oxides of the smelting slags from Ntuha, Mkulusi 1, and 7 sites. The results are normalised to 100 wt%, and the areas were measured at *x*50

Sample	Area	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	MnO	FeO	BaO	Total
TzNtuha2 SE1	Area 1	0.4	0.5	10.0	27.0	0.4	0.3	1.9	3.9	0.3	3.7	52.8	0.3	101
	Area 2	0.3	0.8	9.8	27.3	0.3	0.0	2.1	3.0	0.2	4.0	53.8	0.4	102
	Area 3	0.3	0.8	8.5	27.8	0.4	0.3	1.8	3.5	0.1	3.8	52.9	0.4	100
	Average	0.3	0.7	9.4	27.4	0.4	0.2	1.9	3.5	0.2	3.8	53.2	0.4	101
TzNtuha2 SE2	Area 1	0.0	0.6	7.2	15.2	0.4	0.1	0.9	3.8	0.4	3.5	69.1	-0.3	101
	Area 2	0.1	0.4	7.0	13.4	0.1	0.0	0.8	3.8	0.4	3.1	72.0	0.0	101
	Area 3	0.1	0.5	4.7	13.1	0.3	0.0	0.7	3.6	0.1	3.1	74.1	0.2	100
	Average	0.0	0.5	6.3	13.9	0.3	0.0	0.8	3.7	0.3	3.2	71.7	0.0	101
TzNtuha2 SE3	Area 1	0.1	0.6	4.4	10.0	0.2	-0.1	0.5	0.7	0.1	3.2	80.7	0.3	101
	Area 2	0.0	0.9	2.2	7.8	0.0	0.2	0.3	0.4	0.0	2.2	85.6	0.3	100
	Area 3	0.1	0.8	2.0	5.5	0.0	-0.1	0.2	0.6	0.3	1.6	88.6	-0.2	99
	Average	0.1	0.7	2.8	7.8	0.1	0.0	0.3	0.6	0.1	2.3	85.0	0.1	100
TzNtuha1 SE4	Area 1	0.0	0.7	6.2	27.3	0.4	0.2	0.5	1.4	0.1	3.0	59.7	0.1	100
	Area 2	0.1	0.7	5.8	27.6	0.2	0.1	0.8	1.3	0.2	3.1	59.7	0.3	100
	Area 3	0.2	0.8	7.3	23.7	0.3	0.1	0.7	1.0	0.3	3.3	62.3	0.2	100

	Average	0.1	0.7	6.4	26.2	0.3	0.1	0.7	1.2	0.2	3.1	60.6	0.2	100
TzNtuhaS SE5	Area 1	0.1	0.4	6.9	28.8	0.2	0.0	1.3	1.4	0.3	3.6	56.6	0.3	100
	Area 2	0.1	0.4	5.7	26.9	-0.1	0.0	1.2	1.0	0.0	3.8	61.2	0.1	100
	Area 3	0.1	0.7	6.2	26.8	0.2	-0.1	0.9	0.7	0.1	3.7	60.3	0.3	100
	Average	0.1	0.5	6.3	27.5	0.1	0.0	1.1	1.1	0.1	3.7	59.4	0.3	100
TzMkulusi7 SE1	Area 1	0.1	0.7	8.6	40.5	0.6	0.0	1.2	4.7	0.9	0.3	43.4	0.1	101
	Area 2	0.1	0.7	8.8	41.7	0.4	0.0	1.3	4.8	0.9	0.1	42.0	0.3	101
	Area 3	-0.1	0.8	7.5	41.8	0.6	0.0	1.2	4.5	1.0	0.1	43.0	0.0	100
	Average	0.0	0.7	8.3	41.3	0.5	0.0	1.2	4.7	0.9	0.2	42.8	0.1	101
TzMkulusi7 SE2	Area 1	0.0	1.0	7.5	40.9	0.9	0.1	1.6	2.9	0.8	0.2	43.7	0.2	100
	Area 2	0.0	0.9	8.5	40.6	0.6	0.0	1.5	2.4	1.0	0.1	45.1	0.1	101
	Area 3	0.2	0.8	7.4	40.3	0.8	0.2	1.5	2.7	0.9	0.3	44.3	0.1	100
	Average	0.1	0.9	7.8	40.6	0.8	0.1	1.6	2.7	0.9	0.2	44.4	0.1	100
TzMkulusi7 SE3	Area 1	0.1	0.5	7.8	50.7	0.6	0.0	1.7	1.7	1.7	0.2	35.2	0.0	100
	Area 2	-0.1	0.6	7.4	40.1	0.6	0.0	1.2	1.5	1.1	0.1	48.0	0.0	100
	Area 3	0.0	0.6	7.4	40.7	0.5	0.0	1.2	1.5	1.1	0.1	46.8	0.0	100
	Average	0.0	0.6	7.5	43.9	0.5	0.0	1.4	1.6	1.3	0.1	43.4	0.0	100
TzMkulusi7 SE4	Area 1	0.1	1.1	7.6	40.8	1.0	0.0	1.8	3.4	1.0	0.0	44.1	0.0	101
	Area 2	0.1	1.0	6.8	41.7	0.8	0.0	1.6	2.4	1.2	0.2	44.3	0.0	100
	Area 3	0.0	1.2	7.5	39.8	1.1	0.0	1.8	3.4	1.0	0.2	44.9	0.0	100
	Average	0.0	1.1	7.3	40.8	1.0	0.0	1.7	3.1	1.1	0.1	44.4	0.0	100
TzMkulusi7 SE5	Area 1	0.0	1.0	7.9	40.4	0.7	0.0	1.6	2.7	0.9	0.1	44.9	0.1	100
	Area 2	0.0	1.0	7.6	40.3	1.1	0.0	1.7	3.2	0.9	0.2	43.9	0.2	100
	Area 3	0.0	0.9	8.5	39.9	1.0	0.3	1.8	2.8	1.0	0.1	44.2	0.3	101
	Average	0.0	0.9	8.0	40.2	0.9	0.1	1.7	2.9	0.9	0.1	44.3	0.2	100
TzMkulusi1 SE1	Area 1	0.1	0.8	10.0	44.6	0.5	0.2	2.0	2.2	1.1	0.9	37.4	0.2	100
	Area 2	0.0	1.0	10.0	44.7	0.5	0.0	2.0	2.3	0.9	0.8	37.6	0.1	100
	Area 3	0.0	1.0	10.0	44.6	0.5	0.0	2.0	2.2	1.3	1.0	37.5	-0.2	100
	Average	0.0	0.9	10.0	44.6	0.5	0.1	2.0	2.3	1.1	0.9	37.5	0.1	100
TzMkulusi1 SE2	Area 1	0.1	0.6	8.0	43.4	0.4	0.1	1.4	2.4	1.2	0.2	41.8	0.3	100
	Area 2	0.0	0.6	7.9	43.9	0.2	0.0	1.4	2.4	1.4	0.1	42.2	-0.2	100
	Area 3	-0.1	0.6	7.6	44.4	0.4	0.1	1.4	2.4	1.4	0.2	41.8	-0.2	100
	Average	0.0	0.6	7.8	43.9	0.4	0.1	1.4	2.4	1.3	0.1	41.9	0.0	100
TzMkulusi1 SE3	Area 1	0.2	0.6	8.5	38.5	1.0	0.2	1.2	3.8	1.2	0.1	44.7	0.0	100
	Area 2	0.0	0.6	8.3	38.6	1.0	0.0	1.2	3.4	1.1	0.2	45.5	0.0	100
	Area 3	0.1	0.8	8.1	37.8	0.9	0.1	1.4	3.5	1.0	0.3	45.9	0.2	100
	Average	0.1	0.7	8.3	38.3	1.0	0.1	1.2	3.6	1.1	0.2	45.4	0.1	100
TzMkulusi1 SE4	Area 1	0.2	0.5	7.4	42.2	0.5	0.1	1.2	2.1	1.3	0.0	44.8	-0.3	100
	Area 2	0.2	0.5	8.2	41.6	0.5	-0.2	1.3	2.4	1.3	0.1	44.1	-0.1	100
	Area 3	0.1	0.7	8.0	41.8	0.4	0.0	1.3	2.2	1.2	0.1	44.1	0.0	100
	Average	0.1	0.6	7.9	41.9	0.5	0.0	1.3	2.2	1.3	0.1	44.4	-0.1	100
TzMkulusi1 SE5	Area 1	0.1	0.4	5.0	43.0	0.6	0.3	1.2	1.8	1.0	0.0	46.6	0.1	100
	Area 2	0.1	0.3	5.1	46.4	0.3	0.1	1.1	1.3	0.9	0.2	44.1	0.1	100
	Area 3	0.2	0.5	4.8	44.1	0.5	-0.1	1.0	1.5	1.0	0.1	46.2	0.2	100
	Average	0.1	0.4	5.0	44.5	0.5	0.1	1.1	1.5	1.0	0.1	45.6	0.1	100

Appendix 7.14: Full results of the (P) XRF-EDS trace oxide concentrations of the smelting slags from Ntuha, Mkulusi 1, and Mkulusi 7 sites. Note the results are not normalised to 100 wt%

Sample	Co3O4	NiO	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Ba	Ce	Hf	Ta2O5	WO3	Th	U
TzMkulusi1 SE1	155	6	21	6	73	25	121	8	548	73	8	8	100	6	9
TzMkulusi1 SE1_r01	77	6	17	9	76	26	126	10	562	76	8	7	95	6	9
TzMkulusi1 SE1_r02	96	6	17	5	72	26	118	9	551	72	8	9	74	6	10
Average	109	6	18	7	74	25	122	9	554	74	8	8	89	6	9
TzMkulusi1 SE2	110	7	20	6	67	22	146	4	93	34	10	9	90	7	9
TzMkulusi1 SE2_r01	110	7	14	7	68	23	156	5	94	31	10	9	77	7	8
TzMkulusi1 SE2_r02	110	7	18	7	69	21	157	5	86	28	9	9	87	7	8
Average	110	7	18	6	68	22	153	5	91	31	9	9	85	7	8
TzMkulusi1 SE3	120	9	40	9	80	24	97	11	73	31	12	18	43	9	10
TzMkulusi1 SE3_r01	120	8	30	11	80	26	88	7	69	22	12	33	16	9	9
TzMkulusi1 SE3_r02	120	9	31	8	79	25	96	10	70	26	12	25	15	9	8
Average	120	9	34	9	80	25	94	9	71	26	12	25	25	9	9
TzMkulusi1 SE4	110	7	22	8	64	22	140	9	82	35	9	9	14	8	12
TzMkulusi1 SE4_r01	228	7	17	10	63	20	138	6	80	26	9	17	14	8	9
TzMkulusi1 SE4_r02	110	7	21	3	60	23	138	10	79	27	10	9	14	8	8
Average	149	7	20	7	63	22	139	8	80	29	10	12	14	8	10
TzMkulusi1 SE5	120	8	20	11	42	23	125	5	65	27	10	17	14	9	8
TzMkulusi1 SE5_r01	120	8	18	11	40	24	132	4	72	54	10	11	13	9	10
TzMkulusi1 SE5_r02	110	8	24	11	41	23	134	4	65	33	10	10	13	8	16
Average	117	8	21	11	41	24	130	4	67	38	10	13	13	8	11
TzMkulusi7 SE1	110	8	35	7	145	24	80	14	95	32	10	15	65	7	10
TzMkulusi7 SE1_r01	110	8	31	11	144	23	74	12	88	37	10	14	61	7	7
TzMkulusi7 SE1_r02	110	8	36	10	142	24	79	14	88	47	11	12	69	7	9
Average	110	8	34	9	144	24	78	13	90	39	10	14	65	7	9
TzMkulusi7 SE2	120	8	24	5	80	25	101	7	85	36	10	10	80	8	13
TzMkulusi7 SE2_r01	120	7	15	8	81	25	98	8	77	51	10	9	92	8	11
TzMkulusi7 SE2_r02	120	8	15	3	83	25	104	5	70	47	10	10	82	8	10
Average	120	8	18	5	81	25	101	7	77	45	10	10	84	8	12
TzMkulusi7 SE3	120	8	15	6	58	25	97	7	80	34	10	13	53	9	11
TzMkulusi7 SE3_r01	120	8	12	6	55	25	99	7	74	38	10	10	74	9	9
TzMkulusi7 SE3_r02	120	8	18	5	57	26	101	6	77	33	10	10	15	9	9
Average	120	8	15	6	56	25	99	7	77	35	10	11	47	9	9
TzMkulusi7 SE4	110	8	24	7	90	26	108	9	79	50	9	8	53	8	10
TzMkulusi7 SE4_r01	118	7	17	3	87	26	114	9	82	39	10	10	15	8	9
TzMkulusi7 SE4_r02	120	8	16	3	87	26	106	7	86	48	11	19	14	8	10
Average	116	7	19	4	88	26	109	8	82	46	10	12	27	8	9
TzMkulusi7 SE5	110	8	22	3	85	26	107	6	77	37	10	11	16	8	10
TzMkulusi7 SE5_r01	110	7	17	3	85	24	105	9	78	52	10	10	63	8	9
TzMkulusi7 SE5_r02	110	8	22	3	88	26	99	6	84	43	11	9	58	8	8
Average	110	7	20	3	86	25	104	7	80	44	10	10	45	8	9
TzNtuha1 SE4	160	13	31	22	184	31	8	8	386	13	13	13	19	15	11
TzNtuha1 SE4_r01	160	13	20	19	187	31	5	8	385	13	14	15	20	15	9
TzNtuha1 SE4_r02	160	12	22	18	188	30	5	7	383	11	13	14	21	15	14
Average	160	13	24	20	186	31	6	7	385	12	13	14	20	15	11
TzNtuha2 SE1	150	10	20	7	264	37	13	7	616	13	11	11	16	13	10
TzNtuha2 SE1_r01	150	10	12	10	270	37	23	7	617	12	11	10	17	13	12
TzNtuha2 SE1_r02	150	10	11	10	273	39	24	9	623	11	12	10	18	13	9

Average	150	10	14	9	269	38	20	8	619	12	11	10	17	13	10
TzNtuha2 SE2	190	15	16	10	79	18	6	7	228	12	15	20	26	21	13
TzNtuha2 SE2_r01	190	15	22	5	79	18	6	7	220	12	17	14	20	21	12
TzNtuha2 SE2_r02	190	14	24	5	83	20	5	7	227	12	17	15	36	21	12
Average	190	15	20	7	80	19	5	7	225	12	16	16	27	21	12
TzNtuha2 SE3	180	15	24	5	84	20	11	8	341	12	17	15	23	20	10
TzNtuha2 SE3_r01	180	17	14	8	88	20	10	8	336	13	15	23	24	20	13
TzNtuha2 SE3_r02	190	17	23	5	87	19	4	8	343	12	15	16	23	20	12
Average	183	16	20	6	86	19	8	8	340	12	16	18	23	20	12
TzNtuhaS SE5	160	11	21	22	271	25	51	6	803	12	13	13	16	14	11
TzNtuhaS SE5_r01	160	12	12	22	271	28	51	6	799	12	14	12	16	14	11
TzNtuhaS SE5_r02	160	11	8	25	264	27	49	6	801	11	12	12	16	14	11
Average	160	11	14	23	269	26	50	6	801	12	13	12	16	14	11

Appendix 7.15: Full results of the SEM-EDS chemical composition (in wt%) of fayalitic crystals in the smelting slags from Ntuha and Mkulusi 1 and 2 sites. Note the results are normalised to 100 wt%

Sample	Spectrum	MgO	Al203	SiO2	P2O5	K2O	CaO	TiO2	MnO	FeO	Total
TzNtuha2 SE1	Spectrum 1	1.1	0.1	31.5	0.0	0.0	1.6	0.0	6.1	59.7	100
	Spectrum 2	1.2	0.0	31.6	0.2	0.0	1.3	0.0	6.5	59.3	100
	Spectrum 3	0.9	0.1	31.4	0.2	0.0	1.4	0.0	6.4	59.7	100
	Average	1.1	0.0	31.5	0.1	0.0	1.4	0.0	6.4	59.6	100
TzNtuha2 SE2	Spectrum 1	2.1	0.1	31.1	0.3	0.0	2.7	0.0	8.9	54.9	100
	Spectrum 2	2.4	0.0	31.4	0.0	0.0	2.5	0.0	9.0	54.7	100
	Spectrum 3	2.3	0.1	31.3	0.1	0.0	2.7	0.0	9.0	54.6	100
	Average	2.2	0.1	31.3	0.1	0.0	2.6	0.0	9.0	54.7	100
TzNtuha2 SE3	Spectrum 1	1.3	0.1	31.1	0.0	0.0	0.5	0.1	6.1	60.9	100
	Spectrum 2	3.0	0.1	31.9	0.0	0.0	0.4	0.0	6.5	58.2	100
	Spectrum 3	1.2	0.2	31.2	0.1	0.0	0.5	0.0	6.0	60.8	100
	Average	1.9	0.1	31.4	0.0	0.0	0.5	0.0	6.2	60.0	100
TzNtuha1 SE4	Spectrum 1	1.6	0.3	31.5	0.2	0.1	1.3	0.0	4.1	60.9	100
	Spectrum 2	1.2	0.1	31.3	0.1	0.1	2.2	0.1	4.0	60.9	100
	Spectrum 3	2.1	0.3	31.3	0.2	0.0	0.5	0.0	4.3	61.4	100
	Average	1.6	0.2	31.4	0.2	0.1	1.3	0.0	4.1	61.1	100
TzNtuhaS SE5	Spectrum 1	1.9	0.3	30.7	0.4	0.0	0.2	0.0	5.7	60.9	100
	Spectrum 2	2.1	0.0	31.1	0.2	0.0	0.1	0.1	5.7	60.7	100
	Spectrum 3	1.0	0.1	31.0	0.1	0.0	0.3	0.1	6.1	61.4	100
	Average	1.7	0.1	30.9	0.3	0.0	0.2	0.0	5.8	61.0	100
TzMkulusi7 SE1	Spectrum 1	2.3	0.0	31.9	0.4	0.0	0.4	0.1	0.2	64.7	100
	Spectrum 2	2.4	0.0	32.2	-0.1	0.0	0.4	0.2	0.2	64.7	100
	Spectrum 3	2.8	0.0	32.2	0.1	0.0	0.4	0.1	0.2	64.3	100
	Average	2.5	0.0	32.1	0.1	0.0	0.4	0.1	0.2	64.6	100
TzMkulusi7 SE2	Spectrum 1	1.8	0.1	31.4	0.5	0.0	0.2	0.1	0.1	65.8	100

	Spectrum 2	1.9	0.0	31.5	0.3	0.0	0.2	0.2	0.2	65.6	100
	Spectrum 3	2.1	0.0	31.9	0.3	0.0	0.4	0.3	0.3	64.9	100
	Average	2.0	0.0	31.6	0.4	0.0	0.3	0.2	0.2	65.4	100
TzMkulusi7 SE3	Spectrum 1	1.4	0.0	31.2	0.1	0.0	0.1	0.1	0.2	66.9	100
	Spectrum 2	1.3	0.0	30.7	0.3	0.0	0.2	0.1	0.2	67.3	100
	Spectrum 3	1.6	0.0	31.0	0.5	0.0	0.2	0.2	0.1	66.5	100
	Average	1.4	0.0	31.0	0.3	0.0	0.2	0.1	0.2	66.9	100
TzMkulusi7 SE4	Spectrum 1	5.0	0.0	31.9	0.2	0.1	0.3	0.1	0.2	62.3	100
	Spectrum 2	5.3	0.0	31.9	0.7	0.0	0.3	0.1	0.3	61.5	100
	Spectrum 3	5.0	0.0	31.8	0.0	0.0	0.5	0.2	0.3	62.2	100
	Average	5.1	0.0	31.9	0.3	0.0	0.4	0.1	0.3	62.0	100
TzMkulusi7 SE5	Spectrum 1	1.3	0.1	31.2	0.3	0.0	0.2	0.1	0.3	66.6	100
	Spectrum 2	2.3	0.1	31.0	0.3	0.0	0.2	0.0	0.3	66.0	100
	Spectrum 3	2.1	0.1	30.7	0.1	0.1	0.3	0.1	0.1	66.5	100
	Average	1.9	0.1	31.0	0.2	0.0	0.2	0.0	0.2	66.3	100
TzMkulusi1 SE1	Spectrum 1	3.1	0.0	31.6	0.0	0.0	0.2	0.0	1.3	63.7	100
	Spectrum 2	3.4	0.1	31.9	0.1	0.0	0.2	0.1	1.5	62.7	100
	Spectrum 3	3.3	0.0	31.7	0.1	0.1	0.3	0.1	1.2	63.3	100
	Average	3.2	0.0	31.7	0.1	0.0	0.2	0.1	1.3	63.2	100
TzMkulusi1 SE2	Spectrum 1	1.2	1.3	34.0	0.2	0.3	0.5	0.4	0.2	61.9	100
	Spectrum 2	0.8	4.5	41.1	0.4	1.2	2.0	1.2	0.1	48.7	100
	Spectrum 3	1.0	3.3	37.6	0.3	0.8	1.1	0.6	0.1	55.1	100
	Average	1.0	3.0	37.5	0.3	0.8	1.2	0.8	0.1	55.3	100
TzMkulusi1 SE3	Spectrum 1	1.1	0.1	31.0	0.1	0.0	0.2	0.1	0.2	67.3	100
	Spectrum 2	1.3	0.0	31.0	-0.1	0.0	0.2	0.1	0.1	67.3	100
	Spectrum 3	1.4	0.1	30.5	0.1	0.0	0.2	0.1	0.2	67.4	100
	Average	1.3	0.1	30.9	0.0	0.0	0.2	0.1	0.2	67.3	100
TzMkulusi1 SE4	Spectrum 1	2.2	0.0	31.5	0.1	0.0	0.2	0.2	0.1	65.8	100
	Spectrum 2	2.0	0.1	31.3	0.2	0.1	0.1	0.2	0.1	66.0	100
	Spectrum 3	2.2	0.1	31.7	0.1	0.0	0.2	0.2	0.2	65.5	100
	Average	2.1	0.0	31.5	0.1	0.0	0.2	0.2	0.1	65.7	100
TzMkulusi1 SE5	Spectrum 1	0.6	2.7	42.8	0.4	1.1	1.1	0.4	-0.1	50.9	100
	Spectrum 2	0.8	2.8	43.0	0.4	1.3	1.3	0.9	0.0	49.4	100
	Spectrum 3	0.8	2.4	42.3	0.2	1.1	0.8	0.4	0.0	51.8	100
	Average	0.7	2.6	42.7	0.3	1.2	1.1	0.6	0.0	50.7	100

Appendix 7.16: Full results of the EPMA composition of iron droplets of the smelting (SE) slags from Mkulusi sites. Note the results are not normalised to 100 wt%

Sample	Si	P	Al	Cu	Ni	Co	Sn	Mn	C	Fe	AT
TzMkulusi1 SE3	0.00	0.15	0.00	0.06	0.06	0.00	0.00	0.00	1.51	99.55	101.32
TzMkulusi1 SE3	0.25	0.10	0.06	0.06	0.08	0.61	0.00	0.00	1.65	98.45	101.26
TzMkulusi1 SE3	0.08	0.01	0.05	0.20	0.28	0.00	0.00	0.00	0.30	97.66	98.58
TzMkulusi1 SE3	0.00	0.01	0.01	0.19	0.41	0.00	0.00	0.00	0.05	99.43	100.09
TzMkulusi1 SE3	0.05	0.04	0.02	0.18	0.03	0.00	0.00	0.00		99.00	99.33
Average	0.08	0.06	0.03	0.14	0.17	0.12	0.00	0.00	0.88	98.83	100.30

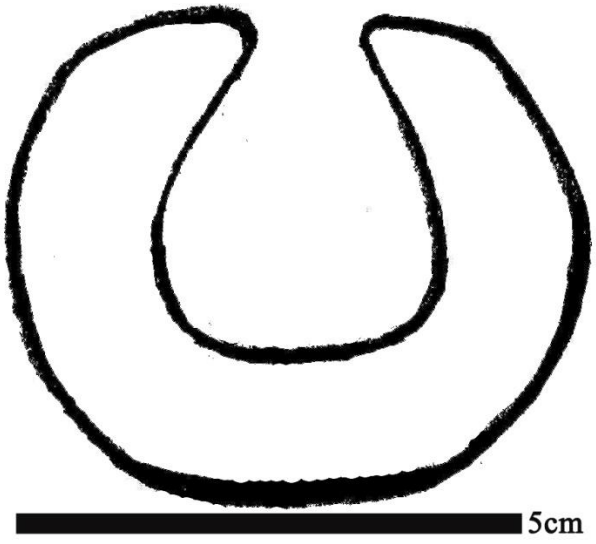
TzMkulusi1 SE1	0.00	0.09	0.00	0.02	0.08	0.00	0.00	0.02	0.66	97.04	97.92
TzMkulusi1 SE1	0.00	0.48	0.00	0.03	0.05	0.00	0.00	0.00	0.69	98.31	99.56
TzMkulusi1 SE1	0.11	0.15	0.06	0.02	0.05	0.27	0.00	0.01	0.66	98.86	100.17
TzMkulusi1 SE1	0.00	0.10	0.00	0.03	0.03	0.00	0.00	0.00	3.11	97.19	100.45
TzMkulusi1 SE1	0.00	0.07	0.00	0.02	0.15	0.45	0.00	0.02	0.06	99.26	100.03
TzMkulusi1 SE1	0.00	0.38	0.00	0.01	0.04	0.00	0.00	0.00	0.00	99.23	99.65
TzMkulusi1 SE1	0.00	0.21	0.00	0.02	0.03	0.00	0.00	0.00	3.30	97.40	100.95
TzMkulusi1 SE1	0.00	0.64	0.00	0.02	0.06	0.00	0.00	0.00	0.49	99.23	100.44
TzMkulusi1 SE1	0.00	0.04	0.00	0.03	0.05	0.00	0.00	0.01		98.61	98.73
Average	0.01	0.24	0.01	0.02	0.06	0.08	0.00	0.01	1.12	98.32	99.87
TzMkulusi1 SE2	0.00	0.34	0.00	0.04	0.04	0.00	0.00	0.00	1.31	97.65	99.38
TzMkulusi1 SE2	0.00	0.27	0.00	0.03	0.05	0.09	0.00	0.01	0.82	99.21	100.48
TzMkulusi1 SE2	0.00	0.32	0.01	0.02	0.03	0.00	0.00	0.00	1.99	98.05	100.42
TzMkulusi1 SE2	0.00	0.01	0.00	0.03	0.17	0.19	0.01	0.00	1.95	96.12	98.48
TzMkulusi1 SE2	0.65	0.03	0.17	0.05	0.09	0.32	0.00	0.00	2.56	95.74	99.61
TzMkulusi1 SE2	0.20	0.01	0.06	0.02	0.29	0.26	0.00	0.00	2.60	96.26	99.70
TzMkulusi1 SE2	0.00	0.80	0.00	0.03	0.05	0.14	0.00	0.00	1.06	98.01	100.08
									1.44	96.72	98.16
									1.66	96.46	98.13
Average	0.12	0.26	0.03	0.03	0.10	0.14	0.00	0.00	1.76	97.29	99.74
TzMkulusi7 SE2	0.01	0.12	0.03	0.03	0.09	0.06	0.00	0.00	0.67	98.39	99.39
TzMkulusi7 SE2	0.01	0.02	0.01	0.02	0.00	0.00	0.00	0.00	0.67	98.61	99.33
TzMkulusi7 SE2	0.00	0.02	0.02	0.03	0.01	0.00	0.00	0.00	2.10	98.11	100.29
TzMkulusi7 SE2	0.02	0.02	0.01	0.03	0.01	0.00	0.00	0.00	0.80	97.81	98.70
TzMkulusi7 SE2	0.32	0.03	0.05	0.26	0.03	0.00	0.00	0.00	2.87	95.38	98.95
TzMkulusi7 SE2	0.01	0.03	0.04	0.02	0.04	0.00	0.00	0.00	0.09	98.71	98.94
Average	0.06	0.04	0.03	0.06	0.03	0.01	0.00	0.00	1.20	97.83	99.27
TzMkulusi7 SE4	0.00	0.00	0.03	0.03	0.01	0.00	0.00	0.00	0.94	95.73	96.73
TzMkulusi7 SE4	0.00	0.01	0.02	0.03	0.05	0.00	0.00	0.00	2.51	94.49	97.12
TzMkulusi7 SE4	0.16	0.03	0.02	0.03	0.06	0.02	0.00	0.00	2.72	96.38	99.42
TzMkulusi7 SE4	0.00	0.01	0.02	0.03	0.02	0.00	0.00	0.00	0.17	95.07	95.30
TzMkulusi7 SE4	0.02	0.04	0.02	0.02	0.00	0.00	0.00	0.02	0.02	97.06	97.20
TzMkulusi7 SE4	0.00	0.01	0.03	0.04	0.05	0.02	0.00	0.00		98.54	98.68
TzMkulusi7 SE4	0.00	0.00	0.02	0.05	1.31	0.24	0.00	0.00		94.45	96.08
TzMkulusi7 SE4	0.00	0.02	0.03	0.01	0.04	0.00	0.00	0.00		98.52	98.62
Average	0.02	0.02	0.02	0.03	0.19	0.03	0.00	0.00	1.27	95.73	97.32
TzMkulusi7 SE1	0.10	0.01	0.01	0.09	0.07	0.02	0.01	0.00	3.74	94.39	98.44
TzMkulusi7 SE1	0.09	0.02	0.03	0.10	0.07	0.00	0.01	0.00	3.74	95.75	99.80
TzMkulusi7 SE1	0.09	0.01	0.02	0.09	0.06	0.00	0.01	0.00	3.63	95.28	99.19
TzMkulusi7 SE1	0.10	0.01	0.02	0.08	0.05	0.00	0.01	0.00	3.92	95.04	99.22
TzMkulusi7 SE1	0.09	0.01	0.03	0.09	0.06	0.00	0.01	0.00	3.81	95.94	100.04
TzMkulusi7 SE1	0.00	0.01	0.01	0.09	0.04	0.00	0.00	0.00	5.13	94.69	99.98
TzMkulusi7 SE1	0.00	0.02	0.02	0.06	0.05	0.00	0.00	0.00	4.22	95.45	99.83
TzMkulusi7 SE1	0.09	1.18	0.01	0.10	0.10	0.00	0.01	0.00	3.75	94.53	99.76
TzMkulusi7 SE1	0.00	0.71	0.02	0.09	0.10	0.02	0.00	0.00	1.86	94.32	97.12
TzMkulusi7 SE1	0.00	1.18	0.03	0.07	0.10	0.00	0.00	0.00		94.84	96.22
TzMkulusi7 SE1	0.10	0.78	0.02	0.07	0.09	0.00	0.02	0.00		97.34	98.40
Average	0.06	0.36	0.02	0.08	0.07	0.00	0.01	0.00	3.76	95.05	99.41

Appendix 8: Chapter 8 Appendices

Appendix 8.1: List of smelting (SE) sites from Kalenga. Note NGO=Ngongwa, LUK=Lukwambe, MAG=Magubike, and DWS=distance to nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	NGOSE1	S (7^0 46.842'), E (35^0 37.360')	450	314	1528	Edwinus Lyaya
2	LUKSE1	S (7^0 45.357'), E (35^0 33.224')	700	380	1542	Pamela Willoughby
3	MAGSE1	S (7^0 45.399'), E (35^0 28.379')	500	79	1564	Pamela Willoughby
4	MAGSE2	S (7^0 45.412'), E (35^0 28.104')	600	254	1571	Pamela Willoughby
5	MAGSE3	S (7^0 45.940'), E (35^0 29.650')	390	201	1514	Zuberi Waitala
6	**Average**		**528**	**246**	**1544**	

Appendix 8.2: Profile of the possible medicinal ceramic container from Kalenga



Appendix 8.3: Full results of the (P) XRF-EDS major and minor element concentrations (in wt%) of technical ceramics from Kalenga smelting sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TB=test briquettes, PTR=pottery, and TYR=tuyère

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMagubike2 FW1	0.59	0.77	34.24	59.04	0.13	0.04	3.81	0.37	0.70	0.01	0.01	0.08	3.08	103
TzMagubike2 FW1_r01	0.55	0.78	34.24	59.07	0.13	0.04	3.80	0.36	0.70	0.01	0.01	0.08	3.08	103
TzMagubike2 FW1_r02	0.83	0.82	34.20	58.85	0.13	0.04	3.78	0.37	0.69	0.01	0.01	0.08	3.06	103
Average	0.66	0.79	34.23	58.99	0.13	0.04	3.79	0.37	0.69	0.01	0.01	0.08	3.07	103
TzMagubike2 FW2	1.04	0.66	32.30	60.60	0.14	0.02	3.86	0.42	0.66	0.01	0.01	0.10	3.04	103
TzMagubike2 FW2_r01	1.05	0.74	32.39	60.49	0.10	0.03	3.86	0.41	0.66	0.01	0.01	0.09	3.02	103
TzMagubike2 FW2_r02	0.87	0.73	32.31	60.69	0.14	0.03	3.84	0.42	0.66	0.01	0.01	0.10	3.05	103
Average	0.99	0.71	32.33	60.59	0.13	0.02	3.85	0.42	0.66	0.01	0.01	0.09	3.03	103
TzMagubike2 FW3	0.63	0.85	34.96	58.70	0.13	0.04	3.71	0.41	0.70	0.01	0.00	0.09	2.63	103
TzMagubike2 FW3_r01	0.77	0.86	34.87	58.72	0.13	0.04	3.66	0.40	0.68	0.01	0.00	0.09	2.63	103
TzMagubike2 FW3_r02	0.55	0.80	35.13	58.73	0.09	0.04	3.67	0.42	0.68	0.01	0.01	0.09	2.63	103
Average	0.65	0.84	34.99	58.72	0.12	0.04	3.68	0.41	0.69	0.01	0.00	0.09	2.63	103
TzMagubike2 TYR1	1.29	0.89	29.43	62.40	0.20	0.01	4.27	0.88	0.63	0.01	0.01	0.11	2.71	103
TzMagubike2 TYR1_r01	0.93	0.85	29.55	62.65	0.20	0.01	4.30	0.86	0.62	0.01	0.02	0.11	2.74	103
TzMagubike2 TYR1_r02	1.01	0.83	29.58	62.59	0.20	0.01	4.27	0.86	0.62	0.01	0.01	0.11	2.73	103
Average	1.08	0.85	29.52	62.55	0.20	0.01	4.28	0.87	0.63	0.01	0.01	0.11	2.73	103
TzMagubike2 TYR2	0.84	0.82	30.83	62.03	0.15	0.02	4.26	0.53	0.68	0.01	0.01	0.11	2.55	103
TzMagubike2 TYR2_r01	0.90	0.80	30.86	61.99	0.16	0.02	4.26	0.51	0.68	0.01	0.01	0.11	2.54	103
TzMagubike2 TYR2_r02	1.24	0.78	30.75	61.81	0.15	0.03	4.23	0.51	0.67	0.01	0.01	0.11	2.55	103
Average	0.99	0.80	30.81	61.94	0.15	0.02	4.25	0.52	0.68	0.01	0.01	0.11	2.55	103
TzMagubike2 TYR3	0.91	0.45	26.67	67.35	0.08	0.02	4.63	0.15	0.53	0.01	0.01	0.04	2.01	103
TzMagubike2 TYR3_r01	1.04	0.45	26.71	67.16	0.08	0.02	4.65	0.16	0.52	0.01	0.01	0.04	2.00	103
TzMagubike2 TYR3_r02	0.76	0.46	26.86	67.25	0.11	0.02	4.66	0.15	0.53	0.01	0.01	0.04	2.00	103
Average	0.90	0.45	26.75	67.25	0.09	0.02	4.65	0.15	0.53	0.01	0.01	0.04	2.00	103
TzMagubike1-2 TYR1	4.37	1.59	17.55	71.88	0.11	0.00	2.34	2.36	0.32	0.01	0.04	0.05	2.28	103
TzMagubike1-2 TY_r01	4.52	1.57	17.65	71.73	0.09	0.00	2.33	2.33	0.32	0.01	0.04	0.05	2.26	103
TzMagubike1-2 TYR2	3.82	3.06	21.95	65.02	0.46	0.01	2.34	2.46	0.49	0.01	0.02	0.05	3.20	103
Average	4.24	2.08	19.05	69.54	0.22	0.00	2.33	2.38	0.38	0.01	0.03	0.05	2.58	103
TzMagubike1-2 TY_r01	3.29	3.05	22.06	65.39	0.46	0.01	2.35	2.48	0.49	0.01	0.02	0.05	3.24	103
TzMagubike1-2 TY_r02	4.38	1.58	17.69	71.74	0.12	0.00	2.35	2.36	0.32	0.01	0.03	0.05	2.26	103

TzMagubike1-2 TY_r02	3.54	3.06	22.17	65.10	0.47	0.01	2.32	2.46	0.48	0.01	0.02	0.05	3.20	103
Average	3.74	2.56	20.64	67.41	0.35	0.01	2.34	2.44	0.43	0.01	0.02	0.05	2.90	103
TzMagubike1-4 TYR3	3.41	1.47	21.20	69.30	0.27	0.01	2.62	1.42	0.38	0.01	0.03	0.03	2.74	103
TzMagubike1-4 TY_r01	4.16	1.53	20.99	68.82	0.27	0.01	2.59	1.38	0.38	0.01	0.02	0.03	2.69	103
TzMagubike1-4 TY_r02	3.67	1.50	21.23	69.05	0.27	0.01	2.59	1.39	0.39	0.00	0.02	0.03	2.72	103
Average	3.75	1.50	21.14	69.06	0.27	0.01	2.60	1.40	0.39	0.01	0.02	0.03	2.72	103
TzNgongwa1 FW1	2.62	1.84	24.96	66.90	0.08	0.01	3.06	1.21	0.37	0.01	0.01	0.06	1.80	103
TzNgongwa1 FW1_r01	2.73	1.75	24.93	66.90	0.07	0.01	3.07	1.21	0.37	0.01	0.01	0.06	1.80	103
TzNgongwa1 FW1_r02	3.02	1.86	24.75	66.67	0.08	0.01	3.07	1.21	0.37	0.01	0.02	0.06	1.80	103
Average	2.79	1.81	24.88	66.82	0.08	0.01	3.07	1.21	0.37	0.01	0.01	0.06	1.80	103
TzNgongwa1 FW2	2.62	1.76	25.20	66.68	0.05	0.01	3.08	1.23	0.38	0.01	0.02	0.06	1.82	103
TzNgongwa1 FW2_r01	2.56	1.84	25.06	66.83	0.08	0.01	3.06	1.22	0.37	0.01	0.01	0.06	1.80	103
TzNgongwa1 FW2_r02	2.62	1.85	25.09	66.74	0.06	0.01	3.05	1.23	0.37	0.00	0.01	0.06	1.82	103
Average	2.60	1.82	25.12	66.75	0.06	0.01	3.06	1.23	0.37	0.01	0.01	0.06	1.81	103
TzNgongwa1 FW3	2.98	2.06	24.16	66.36	0.09	0.01	3.02	1.92	0.37	0.00	0.02	0.07	1.87	103
TzNgongwa1 FW3_r01	2.81	1.96	24.21	66.61	0.09	0.01	2.99	1.91	0.38	0.01	0.02	0.07	1.87	103
TzNgongwa1 FW3_r02	2.85	1.97	24.18	66.55	0.09	0.00	3.01	1.93	0.38	0.01	0.02	0.07	1.87	103
Average	2.88	1.99	24.18	66.51	0.09	0.01	3.01	1.92	0.37	0.01	0.02	0.07	1.87	103
TzNgongwa1 PTR1	3.03	1.25	25.30	66.17	0.08	0.01	2.42	1.15	0.42	0.01	0.01	0.03	3.05	103
TzNgongwa1 PTR1_r01	3.58	1.28	25.23	65.73	0.08	0.01	2.39	1.14	0.42	0.01	0.01	0.03	3.00	103
TzNgongwa1 PTR1_r02	3.09	1.22	25.35	66.10	0.08	0.01	2.43	1.13	0.42	0.01	0.02	0.03	3.03	103
Average	3.23	1.25	25.29	66.00	0.08	0.01	2.41	1.14	0.42	0.01	0.02	0.03	3.03	103
TzNgongwa1 PTR2	3.14	1.23	25.85	65.50	0.06	0.01	2.08	1.22	0.44	0.01	0.01	0.07	3.28	103
TzNgongwa1 PTR2_r01	3.06	1.24	26.00	65.44	0.06	0.01	2.08	1.22	0.44	0.01	0.01	0.07	3.27	103
TzNgongwa1 PTR2_r02	3.40	1.26	25.94	65.18	0.06	0.01	2.08	1.21	0.44	0.01	0.02	0.07	3.26	103
Average	3.20	1.24	25.93	65.37	0.06	0.01	2.08	1.22	0.44	0.01	0.01	0.07	3.27	103
TzNgongwa1 PTR3	3.44	1.25	25.60	65.73	0.03	0.01	2.05	1.20	0.43	0.01	0.01	0.03	3.12	103
TzNgongwa1 PTR3_r01	3.50	1.17	25.67	65.70	0.03	0.01	2.04	1.18	0.44	0.01	0.01	0.03	3.13	103
TzNgongwa1 PTR3_r02	3.27	1.19	25.73	65.84	0.03	0.01	2.07	1.19	0.42	0.01	0.01	0.03	3.12	103
Average	3.40	1.21	25.67	65.76	0.03	0.01	2.05	1.19	0.43	0.01	0.01	0.03	3.12	103
TzNgongwa1 TB1	4.23	1.53	14.76	76.22	0.04	0.00	2.80	1.17	0.25	0.00	0.02	0.06	1.83	103
TzNgongwa1 TB1_r01	4.25	1.43	14.83	76.30	0.05	0.00	2.74	1.15	0.24	0.01	0.02	0.06	1.83	103
TzNgongwa1 TB1_r02	4.16	1.49	14.85	76.26	0.05	0.00	2.78	1.16	0.24	0.01	0.02	0.06	1.83	103
Average	4.21	1.48	14.81	76.26	0.05	0.00	2.78	1.16	0.24	0.01	0.02	0.06	1.83	103
TzNgongwa1 TB2	4.35	1.58	15.49	75.09	0.05	0.01	2.99	1.22	0.25	0.01	0.02	0.05	1.84	103
TzNgongwa1 TB2_r01	4.46	1.50	15.52	75.08	0.04	0.00	2.94	1.22	0.24	0.01	0.02	0.05	1.84	103
TzNgongwa1 TB2_r02	4.28	1.49	15.61	75.11	0.07	0.00	2.97	1.23	0.24	0.01	0.02	0.05	1.85	103
Average	4.36	1.52	15.54	75.09	0.05	0.00	2.96	1.22	0.24	0.01	0.02	0.05	1.84	103

TzNgongwa1 TB3	4.12	1.41	15.62	75.34	0.07	0.00	2.97	1.22	0.24	0.01	0.02	0.05	1.85	103
TzNgongwa1 TB3_r01	3.92	1.53	15.70	75.35	0.05	0.00	2.96	1.23	0.24	0.00	0.03	0.05	1.84	103
TzNgongwa1 TB3_r02	4.53	1.53	15.43	75.07	0.07	0.00	2.91	1.22	0.25	0.01	0.03	0.05	1.82	103
Average	4.19	1.49	15.58	75.25	0.06	0.00	2.95	1.22	0.24	0.01	0.03	0.05	1.84	103
TzNgongwa1 TYR1	0.94	0.56	33.42	64.68	0.03	0.02	1.15	0.10	0.46	0.01	0.01	0.01	1.53	103
TzNgongwa1 TYR1_r01	0.99	0.59	33.54	64.47	0.03	0.02	1.15	0.11	0.46	0.01	0.01	0.01	1.53	103
TzNgongwa1 TYR1_r02	0.75	0.55	33.46	64.81	0.03	0.02	1.18	0.11	0.46	0.01	0.01	0.01	1.53	103
Average	0.89	0.57	33.47	64.65	0.03	0.02	1.16	0.11	0.46	0.01	0.01	0.01	1.53	103
TzNgongwa1 TYR2	1.17	0.61	33.48	64.36	0.03	0.02	1.15	0.11	0.46	0.01	0.01	0.01	1.52	103
TzNgongwa1 TYR2_r01	0.81	0.59	33.62	64.58	0.03	0.02	1.16	0.10	0.46	0.01	0.01	0.01	1.53	103
TzNgongwa1 TYR2_r02	0.91	0.61	33.58	64.50	0.03	0.02	1.17	0.10	0.46	0.01	0.01	0.01	1.52	103
Average	0.96	0.60	33.56	64.48	0.03	0.02	1.16	0.10	0.46	0.01	0.01	0.01	1.52	103
TzNgongwa1 TYR3	0.77	0.61	33.32	64.95	0.03	0.02	1.17	0.10	0.45	0.01	0.01	0.01	1.49	103
TzNgongwa1 TYR3_r01	1.14	0.60	33.12	64.78	0.03	0.02	1.16	0.10	0.45	0.01	0.01	0.01	1.49	103
TzNgongwa1 TYR3_r02	1.15	0.58	33.24	64.72	0.03	0.02	1.13	0.10	0.44	0.01	0.01	0.01	1.48	103
Average	1.02	0.60	33.23	64.82	0.03	0.02	1.16	0.10	0.45	0.01	0.01	0.01	1.49	103

Appendix 8.4: Full results of the (P) XRF-EDS trace element concentrations (in wt%) of technical ceramics from Kalenga smelting sites. Note the results are not normalised to 100 wt%, FW=furnace wall, TB=test briquettes, PTR=pottery, and TYR=tuyère

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	WO3	PbO	Th
TzMagubike2 FW1	35	9	47	47	19	139	112	26	463	13	296	25	57	21	15	35	59
TzMagubike2 FW1_r01	50	3	46	49	17	138	112	26	466	14	298	25	60	21	14	35	59
TzMagubike2 FW1_r02	45	4	45	48	17	138	110	26	469	14	299	24	59	19	9	34	58
Average	43	6	46	48	18	138	111	26	466	14	298	25	59	20	13	35	59
TzMagubike2 FW2	50	7	46	42	18	137	104	26	464	14	291	27	59	19	27	29	54
TzMagubike2 FW2_r01	54	6	51	40	18	137	105	26	467	13	293	26	61	18	24	29	53
TzMagubike2 FW2_r02	48	6	45	41	16	138	105	27	450	14	295	26	59	21	21	29	55
Average	50	7	47	41	17	137	104	26	460	14	293	26	59	19	24	29	54
TzMagubike2 FW3	48	14	76	45	18	135	125	27	413	15	289	26	61	18	18	33	49
TzMagubike2 FW3_r01	47	6	74	43	17	136	126	26	405	14	287	26	60	19	11	32	47

TzMagubike2 FW3_r02	39	10	79	45	17	136	126	26	412	13	289	27	61	17	17	32	48
Average	45	10	76	44	18	136	125	26	410	14	288	26	61	18	15	32	48
TzMagubike2 TYR1	52	5	56	39	16	149	128	27	508	11	310	26	57	25	70	24	67
TzMagubike2 TYR1_r01	37	13	62	40	17	150	130	27	513	10	315	28	62	20	74	26	66
TzMagubike2 TYR1_r02	38	9	60	41	16	150	130	28	510	11	313	28	61	22	71	26	67
Average	42	9	59	40	16	150	130	27	510	11	313	28	60	22	72	25	66
TzMagubike2 TYR2	48	8	45	47	16	152	122	29	517	12	317	26	64	21	35	30	51
TzMagubike2 TYR2_r01	50	9	41	46	14	150	122	29	521	14	316	27	60	23	43	31	52
TzMagubike2 TYR2_r02	41	9	45	46	17	151	121	29	519	11	315	28	65	21	37	30	52
Average	46	9	44	46	16	151	122	29	519	12	316	27	63	22	38	30	52
TzMagubike2 TYR3	33	9	131	28	14	139	92	18	466	12	283	12	32	20	83	24	49
TzMagubike2 TYR3_r01	33	5	126	27	12	138	90	18	476	12	283	13	34	21	77	23	50
TzMagubike2 TYR3_r02	32	5	129	25	13	138	92	18	463	9	280	12	32	18	81	23	50
Average	32	6	128	27	13	138	92	18	468	11	282	12	33	20	80	23	49
TzMagubike1-2 TYR1	44	19	76	33	8	49	228	11	131	2	310	7	13	7	165	12	11
TzMagubike1-2 TY_r01	43	24	79	34	9	47	226	11	122	3	299	8	20	6	166	12	11
TzMagubike1-2 TYR2	48	39	61	46	11	58	242	14	115	2	313	11	25	5	57	13	9
Average	45	27	72	38	9	51	232	12	123	2	307	9	19	6	129	12	10
TzMagubike1-2 TY_r01	57	45	63	50	11	58	247	14	116	3	317	10	18	5	63	13	9
TzMagubike1-2 TY_r02	36	23	72	33	8	48	229	10	126	3	303	7	20	10	170	12	11
TzMagubike1-2 TY_r02	52	41	60	48	11	57	243	14	119	2	317	10	27	7	67	13	9
Average	48	36	65	44	10	54	239	13	120	2	312	9	21	7	100	12	10
TzMagubike1-4 TYR3	35	17	131	28	10	48	215	10	146	3	272	6	10	7	87	14	10
TzMagubike1-4 TY_r01	43	17	127	28	10	48	211	9	140	2	272	6	10	7	88	14	10
TzMagubike1-4 TY_r02	38	19	127	30	9	48	213	10	148	5	272	6	11	12	87	14	10
Average	38	18	129	29	10	48	213	10	145	3	272	6	10	8	87	14	10
TzNgongwa1 FW1	23	30	20	32	11	77	111	11	170	5	251	13	20	8	46	16	11
TzNgongwa1 FW1_r01	33	31	22	31	12	76	111	12	166	4	250	12	21	10	43	16	11
TzNgongwa1 FW1_r02	24	30	20	31	11	76	111	12	165	5	251	13	21	9	43	16	11
Average	27	30	21	31	11	76	111	12	167	5	251	13	21	9	44	16	11

TzNgongwa1 FW2	32	34	24	33	12	77	112	11	171	5	244	12	20	8	42	17	11
TzNgongwa1 FW2_r01	35	29	21	33	11	77	110	11	174	5	241	12	19	8	41	17	11
TzNgongwa1 FW2_r02	30	29	22	33	11	77	111	11	173	5	239	11	13	8	44	17	10
Average	32	31	22	33	12	77	111	11	172	5	241	12	17	8	42	17	11
TzNgongwa1 FW3	33	34	43	31	11	79	114	11	147	6	233	13	20	8	75	14	10
TzNgongwa1 FW3_r01	39	34	45	33	12	79	112	11	149	4	232	13	20	7	76	14	11
TzNgongwa1 FW3_r02	39	38	42	32	12	79	113	12	143	5	234	13	12	9	84	13	10
Average	37	36	43	32	12	79	113	11	147	5	233	13	17	8	78	13	10
TzNgongwa1 PTR1	51	23	24	27	12	46	118	9	61	4	285	7	16	4	92	14	8
TzNgongwa1 PTR1_r01	35	28	22	29	12	45	117	9	62	1	288	6	22	5	100	14	8
TzNgongwa1 PTR1_r02	46	26	23	28	13	45	117	9	62	3	284	6	14	4	101	15	7
Average	44	25	23	28	12	45	117	9	62	3	286	6	17	5	98	14	8
TzNgongwa1 PTR2	47	27	26	28	13	44	121	10	71	3	275	6	49	4	79	22	8
TzNgongwa1 PTR2_r01	65	22	24	27	12	44	119	10	71	2	273	6	47	4	76	23	8
TzNgongwa1 PTR2_r02	52	27	24	27	12	44	119	10	63	4	274	6	48	4	85	24	8
Average	54	26	24	27	13	44	120	10	68	3	274	6	48	4	80	23	8
TzNgongwa1 PTR3	43	24	21	27	13	45	117	9	69	4	286	6	28	5	75	16	7
TzNgongwa1 PTR3_r01	58	24	20	29	13	46	117	10	65	3	287	6	31	4	72	16	9
TzNgongwa1 PTR3_r02	45	24	21	27	13	46	118	10	67	4	288	8	20	5	84	15	7
Average	49	24	21	28	13	46	117	10	67	3	287	7	26	5	77	16	8
TzNgongwa1 TB1	41	32	13	26	7	56	96	10	233	4	211	8	20	11	94	16	10
TzNgongwa1 TB1_r01	41	32	14	26	8	56	95	10	224	3	214	11	20	9	99	16	10
TzNgongwa1 TB1_r02	36	31	11	23	6	57	96	10	230	3	214	8	14	10	94	16	10
Average	39	32	12	25	7	56	96	10	229	3	213	9	18	10	95	16	10
TzNgongwa1 TB2	24	32	20	27	8	58	99	11	224	3	233	11	11	9	39	16	9
TzNgongwa1 TB2_r01	26	35	19	27	8	58	99	10	227	3	233	9	19	10	40	17	9
TzNgongwa1 TB2_r02	31	32	15	27	8	59	100	10	223	2	234	9	12	10	44	17	9
Average	27	33	18	27	8	58	99	10	224	3	233	10	14	10	41	17	9
TzNgongwa1 TB3	31	32	21	28	8	59	101	10	226	2	228	8	11	9	46	17	9
TzNgongwa1 TB3_r01	31	36	17	25	8	59	100	11	227	3	232	9	17	10	48	16	8

TzNgongwa1 TB3_r02	25	36	19	27	8	58	98	10	220	2	231	10	12	9	45	17	9
Average	29	34	19	27	8	58	100	11	224	2	230	9	13	9	46	17	9
TzNgongwa1 TYR1	30	6	21	31	13	51	20	12	176	26	114	13	25	8	125	18	19
TzNgongwa1 TYR1_r01	26	7	26	32	14	51	20	11	181	26	117	15	23	8	126	17	20
TzNgongwa1 TYR1_r02	29	10	26	33	14	51	20	11	178	26	116	11	15	8	133	17	19
Average	28	8	24	32	14	51	20	12	178	26	116	13	21	8	128	17	19
TzNgongwa1 TYR2	22	7	24	31	14	52	20	12	177	26	119	14	15	8	128	18	18
TzNgongwa1 TYR2_r01	24	8	24	31	14	51	20	12	177	24	119	12	17	9	128	17	18
TzNgongwa1 TYR2_r02	28	8	24	32	14	51	20	12	186	24	122	10	19	9	129	18	18
Average	25	8	24	31	14	51	20	12	180	25	120	12	17	9	128	18	18
TzNgongwa1 TYR3	30	11	23	34	15	52	20	11	181	26	116	13	16	9	165	16	19
TzNgongwa1 TYR3_r01	29	8	23	34	14	51	20	12	183	27	114	12	24	8	157	17	19
TzNgongwa1 TYR3_r02	21	9	23	32	14	51	20	11	180	26	117	13	21	10	169	16	19
Average	27	9	23	34	14	51	20	11	181	26	115	13	20	9	163	16	19

Appendix 8.5: SEM-EDS semi-bulk area composition of the major and minor oxides of the smelting (SE) slags from the Kalenga sites. Note the results are the averages of three areas measured at *x*200, and are normalised to 100 wt%

Sample/ Oxides	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	V2O5	MnO	FeO	ZrO2	Total
TzNgongwa SE5	0.8	0.4	5.1	25.9	0.1	2.2	1.8	0.9	0.2	0.3	57.5	4.7	101
TzNgongwa SE6	0.8	0.4	5.8	31.6	0.0	2.3	1.7	1.5	0.1	0.2	52.2	4.2	101
TzNgongwa SE7	0.5	0.4	4.4	22.6	0.1	2.0	1.6	1.4	0.1	0.2	61.3	5.7	100
S1-Ngon-EA1	0.4	0.5	5.4	29.0	0.0	2.0	1.6	1.2	0.0	0.3	54.4	5.1	100
S1-Ngon-SA1	0.8	0.2	6.3	29.3	0.1	2.7	1.6	1.4	0.2	0.2	52.7	4.3	100
TzMagubike1-1 SE1	0.5	0.6	3.1	16.9	0.2	1.0	6.3	0.3	0.1	0.1	70.2	0.4	89
TzMagubike1-2 SE2	1.0	2.0	6.2	29.3	0.7	1.9	24.2	0.2	-0.1	0.0	34.8	0.0	97
TzMagubike1-2 SE3	0.6	0.9	4.2	19.0	0.3	1.6	7.7	0.6	0.1	0.2	62.2	3.0	174
TzMagubike1-3 SE4	0.5	0.9	3.0	12.3	0.1	0.7	9.0	0.1	0.1	0.0	73.5	0.0	72
TzMagubike1-4 SE5	1.2	0.4	6.3	25.2	0.2	1.7	2.9	0.2	-0.1	0.1	62.2	0.2	101
TzMagubike2 SE1	0.3	0.3	4.2	26.4	0.1	2.2	1.6	0.5	0.2	0.1	60.7	3.3	100
TzMagubike2 SE2	0.2	0.3	4.4	28.2	0.1	2.3	1.3	0.5	0.2	0.1	59.5	2.5	100
TzMagubike2 SE3	0.2	0.3	5.1	27.7	0.2	2.5	1.1	0.4	0.3	0.2	59.8	2.3	100
TzMagubike2 SE4	0.1	0.3	4.1	20.4	0.1	1.8	1.0	0.3	0.2	0.1	70.0	2.0	100
TzMagubike2 SE5	0.1	0.3	3.6	21.2	0.1	1.6	0.7	0.3	0.2	0.1	69.7	1.8	100

Appendix 8.6: Full results of the SEM-EDS bulk area composition of the major and minor oxides (in wt%) of the smelting slags from Kalenga sites. The results are normalised to 100 wt%

	Area	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	TiO2	V2O5	MnO	FeO	ZrO2	Total
TzNgongwa SE5	Area 1	0.7	0.4	5.3	25.5	0.3	2.2	1.7	1.0	0.3	0.2	58.4	4.1	101
	Area 2	0.8	0.3	5.3	25.2	0.2	2.2	1.6	1.0	0.1	0.3	58.2	4.7	100
	Area 3	0.7	0.3	5.6	25.2	0.2	2.2	1.7	1.1	0.1	0.1	58.4	4.4	101
	Mean	0.7	0.3	5.4	25.3	0.2	2.2	1.7	1.0	0.2	0.2	58.3	4.4	101
TzNgongwa SE6	Area 1	0.9	0.6	6.2	31.0	0.3	2.1	1.4	1.5	0.2	0.2	52.1	3.4	101
	Area 2	0.7	0.4	5.7	30.6	0.1	2.0	1.6	1.6	0.1	0.2	52.9	4.0	100
	Area 3	0.8	0.6	5.1	30.7	0.4	2.0	1.7	1.3	0.2	0.1	53.6	3.6	100
	Mean	0.8	0.5	5.7	30.8	0.3	2.0	1.6	1.5	0.2	0.2	52.9	3.7	100
TzNgongwa SE7	Area 1	0.3	0.4	4.5	22.7	0.1	2.0	1.5	1.3	0.3	0.2	60.9	5.8	101
	Area 2	0.5	0.4	4.7	23.0	0.1	2.0	1.6	1.2	0.1	0.2	60.5	5.5	100
	Area 3	0.4	0.4	4.4	23.0	0.0	2.0	1.7	1.3	0.2	0.3	60.2	6.0	101
	Mean	0.4	0.4	4.6	22.9	0.1	2.0	1.6	1.2	0.2	0.3	60.6	5.8	101
S1-Ngon-EA1	Area 1	0.5	0.4	6.1	28.5	0.4	2.1	1.6	1.2	0.1	0.1	53.9	5.2	100
	Area 2	0.6	0.5	6.4	28.7	0.1	2.1	1.6	1.3	0.0	0.1	52.8	5.7	101

	Area 3	0.6	0.5	6.2	28.6	0.2	1.5	1.8	1.3	-0.1	0.3	53.9	5.3	100
	Mean	0.6	0.5	6.2	28.6	0.2	1.9	1.6	1.3	0.0	0.2	53.5	5.4	101
S1-Ngon-SA1	Area 1	0.4	0.3	5.1	25.5	-0.1	2.2	1.4	1.3	0.2	0.2	59.0	4.7	100
	Area 2	0.6	0.3	7.4	24.7	0.0	2.5	1.4	1.2	0.3	0.2	57.4	4.2	101
	Area 3	0.7	0.3	5.8	25.4	0.5	2.4	1.5	1.3	0.0	0.0	58.4	3.6	100
	Mean	0.5	0.3	6.1	25.2	0.1	2.4	1.4	1.2	0.1	0.1	58.2	4.2	101
TzMagubike1-1 SE1	Area 1	0.7	0.9	2.7	18.4	0.2	1.2	6.3	0.3	-0.1	0.0	68.9	0.5	97
	Area 2	0.6	0.8	3.3	17.7	0.3	1.1	7.2	0.2	0.0	0.1	68.2	0.4	91
	Area 3	0.5	0.7	4.4	20.6	0.3	1.4	7.2	0.2	-0.1	0.1	64.5	0.1	92
	Mean	0.6	0.8	3.5	18.9	0.2	1.2	6.9	0.3	0.0	0.1	67.2	0.3	93
TzMagubike1-2 SE2	Area 1	1.0	2.9	6.1	29.7	1.1	3.6	28.2	0.1	0.1	0.2	27.2	-0.3	91
	Area 2	1.0	2.0	7.2	30.0	1.1	2.6	24.7	0.2	0.0	0.1	31.2	-0.1	96
	Area 3	0.9	1.1	4.7	22.1	0.9	1.4	18.7	0.1	0.0	0.0	50.3	-0.1	97
	Mean	1.0	2.0	6.0	27.3	1.0	2.6	23.9	0.1	0.0	0.1	36.2	-0.2	95
TzMagubike1-2 SE3	Area 1	0.2	0.7	4.3	17.3	-0.3	1.3	3.4	0.5	0.0	0.2	68.1	4.1	101
	Area 2	0.2	1.1	4.9	21.1	0.5	1.9	9.7	0.4	-0.1	0.2	57.5	2.5	102
	Area 3	0.5	1.1	4.4	18.4	0.3	1.8	10.3	0.4	0.0	0.1	59.8	2.9	102
	Mean	0.3	1.0	4.5	18.9	0.2	1.7	7.8	0.4	0.0	0.2	61.8	3.2	102
TzMagubike1-3 SE4	Area 1	0.4	1.1	3.6	14.2	-0.1	0.7	9.8	0.3	0.0	0.2	69.9	-0.1	98
	Area 2	0.5	0.8	3.4	15.3	0.3	0.9	11.7	0.1	0.2	0.1	66.4	0.2	99
	Area 3	0.6	0.9	1.3	8.2	0.2	0.4	5.3	0.0	0.1	0.2	82.3	0.3	97
	Mean	0.5	1.0	2.8	12.6	0.1	0.7	8.9	0.1	0.1	0.1	72.8	0.2	98
TzMagubike1-4 SE5	Area 1	1.1	0.4	6.2	24.6	0.1	1.6	2.7	0.0	0.0	0.1	62.9	0.3	109
	Area 2	1.3	0.4	5.5	24.0	0.4	1.5	2.6	0.1	0.0	0.1	64.0	0.1	106
	Area 3	1.5	0.3	6.7	26.4	0.4	1.7	3.1	0.1	-0.2	0.0	59.9	0.1	106
	Mean	1.3	0.4	6.1	25.0	0.3	1.6	2.8	0.1	0.0	0.0	62.3	0.2	107
TzMagubike2 SE1	Area 1	0.1	0.1	5.1	27.5	0.3	2.6	1.7	0.4	0.1	0.3	58.3	3.4	101
	Area 2	0.1	0.3	4.4	26.6	0.3	2.1	1.6	0.4	0.2	0.1	60.3	3.5	100
	Area 3	0.1	0.3	3.5	27.8	0.0	2.4	1.7	0.5	0.1	0.1	59.6	4.0	99
	Mean	0.1	0.2	4.3	27.3	0.2	2.4	1.7	0.4	0.1	0.2	59.4	3.6	100
TzMagubike2 SE2	Area 1	0.2	0.4	5.1	27.6	0.0	2.3	1.1	0.6	0.1	0.0	60.1	2.5	101
	Area 2	0.5	0.2	4.7	28.4	0.0	2.3	1.2	0.4	0.1	0.0	59.8	2.5	100
	Area 3	0.4	0.3	5.7	28.3	0.2	2.6	1.2	0.4	0.3	0.3	57.6	2.7	101
	Mean	0.4	0.3	5.2	28.1	0.1	2.4	1.2	0.5	0.2	0.1	59.1	2.6	100
TzMagubike2 SE3	Area 1	-0.1	0.9	2.6	24.1	-1.0	0.9	0.8	-0.1	0.3	0.5	67.6	3.6	101
	Area 2	0.2	0.2	5.8	27.8	0.6	2.6	1.0	0.4	0.2	0.1	59.0	2.1	101
	Area 3	0.1	0.1	4.5	27.9	0.4	2.5	1.1	0.6	0.0	0.0	60.6	2.3	100
	Mean	0.1	0.4	4.3	26.6	0.0	2.0	1.0	0.3	0.2	0.2	62.4	2.7	100
TzMagubike2 SE4	Area 1	0.3	0.1	3.3	20.9	0.2	1.8	0.8	0.5	0.2	0.0	69.9	1.9	99
	Area 2	0.2	0.3	5.0	20.0	0.1	1.8	1.0	0.5	0.2	0.1	68.8	2.1	101
	Area 3	0.2	0.3	5.0	20.5	0.1	1.7	0.8	0.5	0.3	0.0	68.5	2.0	101
	Mean	0.2	0.2	4.4	20.5	0.1	1.8	0.9	0.5	0.2	0.1	69.1	2.0	101
TzMagubike2 SE5	Area 1	0.4	0.3	3.7	20.7	0.3	1.9	0.8	0.3	0.2	0.3	69.0	2.1	100

	Area 2	0.2	0.3	4.3	20.1	0.1	1.7	0.7	0.5	0.0	0.2	69.3	2.5	100
	Area 3	0.1	0.4	4.4	20.2	0.0	1.6	0.7	0.4	0.3	0.2	69.8	2.0	101
	Mean	0.2	0.3	4.1	20.3	0.1	1.7	0.7	0.4	0.2	0.2	69.4	2.2	100

Appendix 8.7: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting slags from Kalenga sites. Note the results are not normalised to 100 wt%

Sample	Co3O4	NiO	CuO	ZnO	SrO	Y	ZrO2	Nb2O5	Mo	Ba	Ce	Hf	Ta2O5	WO3	PbO	Th	U
TzNgongwa1 EA1	140	10	13	15	148	99	15560	11	37	359	294	465	15	16	7	12	30
TzNgongwa1 EA1_r01	130	11	13	15	152	99	15750	10	34	340	294	505	28	16	8	12	44
TzNgongwa1 EA1_r02	130	10	14	20	151	99	16000	13	33	339	289	459	15	15	7	12	38
Average	133	10	13	16	150	99	15770	11	35	346	292	476	19	16	7	12	37
TzNgongwa1 SA1	172	13	18	10	75	50	7725	10	23	181	124	297	22	19	10	17	32
TzNgongwa1 SA1_r01	160	11	25	5	76	48	7821	10	23	179	122	273	16	20	10	17	34
TzNgongwa1 SA1_r02	160	12	24	5	75	49	7672	10	25	177	130	298	17	19	10	17	32
Average	164	12	22	7	75	49	7739	10	24	179	125	289	18	19	10	17	33
TzNgongwa1 SE5	150	11	13	4	125	62	12350	11	31	407	84	332	14	20	9	13	34
TzNgongwa1 SE5_r01	150	11	13	4	124	64	12260	10	28	400	78	355	15	20	8	13	44
TzNgongwa1 SE5_r02	140	11	12	4	128	61	12130	9	26	397	78	320	14	21	8	13	48
Average	147	11	13	4	125	62	12247	10	28	401	80	336	14	20	8	13	42
TzNgongwa1 SE6	130	11	16	24	129	68	11130	9	27	385	227	326	14	18	7	12	40
TzNgongwa1 SE6_r01	130	10	12	22	127	66	10960	10	24	374	233	324	14	19	7	12	35
TzNgongwa1 SE6_r02	130	10	12	27	124	69	10960	11	29	392	225	301	14	18	7	12	18
Average	130	10	13	24	127	67	11017	10	27	384	228	317	14	18	7	12	31
TzNgongwa1 SE7	120	4	6	8	50	28	6646	9	23	152	47	150	6	8	4	6	13
TzNgongwa1 SE7_r01	120	4	6	2	52	28	6775	8	17	149	43	152	6	8	4	6	11
TzNgongwa1 SE7_r02	120	4	6	7	52	30	6828	7	19	149	44	142	6	8	4	6	13
Average	120	4	6	6	51	29	6750	8	20	150	45	148	6	8	4	6	12
TzMagubike1-1 SE1	170	14	47	5	571	20	882	8	8	134	15	17	17	19	10	16	13
TzMagubike1-1 SE_r01	170	14	30	4	571	18	878	9	10	137	20	21	16	19	10	16	19
TzMagubike1-1 SE_r02	190	13	37	5	573	20	847	9	10	134	20	20	17	19	9	16	14
Average	177	14	38	5	572	19	869	9	9	135	18	19	17	19	10	16	15

TzMagubike1-2 SE2	94	22	47	5	1423	24	186	5	5	447	9	9	7	22	3	4	10
TzMagubike1-2 SE_r01	95	19	44	6	1456	26	170	5	4	459	9	9	17	10	3	4	8
TzMagubike1-2 SE_r02	97	20	44	6	1437	25	185	5	5	459	9	9	20	10	3	4	7
Average	95	20	45	5	1439	25	180	5	4	455	9	9	15	14	3	4	8
TzMagubike1-2 SE3	170	14	19	6	394	34	7251	10	22	123	18	251	29	21	10	16	28
TzMagubike1-2 SE_r01	170	13	26	5	380	30	7135	9	23	123	19	269	21	20	10	16	37
TzMagubike1-2 SE_r02	170	14	33	5	394	31	7132	9	25	122	13	211	19	22	10	16	30
Average	170	14	26	5	390	31	7173	9	23	123	17	244	23	21	10	16	31
TzMagubike1-3 SE4	209	349	109	9	645	15	186	7	6	144	12	23	27	25	12	18	19
TzMagubike1-3 SE_r01	180	337	131	8	630	13	188	7	7	127	12	24	29	23	12	18	20
TzMagubike1-3 SE_r02	400	317	128	5	637	12	178	8	6	130	12	22	28	23	11	17	12
Average	263	334	123	7	637	13	184	7	6	134	12	23	28	24	12	18	17
TzMagubike1-4 SE5	160	37	41	6	241	12	385	7	6	145	11	14	17	17	9	14	12
TzMagubike1-4 SE_r01	160	14	51	6	245	12	366	7	6	145	11	14	23	18	9	14	19
TzMagubike1-4 SE_r02	150	12	42	4	242	11	338	6	5	148	11	17	15	16	9	14	10
Average	157	21	45	5	243	12	363	7	6	146	11	15	18	17	9	14	14
TzMagubike2 SE1	150	11	18	5	249	107	10020	10	42	186	105	406	17	20	11	2	94
TzMagubike2 SE1_r01	150	11	13	5	250	110	10470	13	27	181	113	427	16	21	11	2	120
TzMagubike2 SE1_r02	150	12	12	5	252	110	10520	12	26	196	110	401	16	21	11	2	84
Average	150	11	15	5	250	109	10337	12	32	188	110	411	16	21	11	2	99
TzMagubike2 SE2	140	10	12	5	271	106	7183	14	23	651	114	271	24	19	11	2	132
TzMagubike2 SE2_r01	140	10	11	4	268	106	7283	14	23	659	111	266	14	20	11	2	129
TzMagubike2 SE2_r02	140	11	11	5	273	105	7365	14	23	644	118	263	13	20	11	2	118
Average	140	10	11	4	271	106	7277	14	23	651	114	267	17	20	11	2	126
TzMagubike2 SE3	150	11	12	4	231	100	6901	12	19	555	100	288	14	19	11	2	116
TzMagubike2 SE3_r01	150	10	12	4	232	102	7028	14	20	560	94	297	13	18	11	2	124
TzMagubike2 SE3_r02	150	11	12	5	232	104	6980	14	21	559	113	272	14	19	12	2	140
Average	150	11	12	5	232	102	6970	13	20	558	102	286	14	19	11	2	127
TzMagubike2 SE4	138	13	24	5	142	66	5513	10	17	272	72	214	18	23	13	13	80
TzMagubike2 SE4_r01	239	12	13	5	142	69	5599	10	17	273	52	238	15	21	13	12	86
TzMagubike2 SE4_r02	170	14	16	5	142	69	5699	11	18	276	71	244	17	22	13	13	77

Average	182	13	18	5	142	68	5604	10	17	274	65	232	17	22	13	13	81
TzMagubike2 SE5	170	13	20	5	155	70	5831	13	21	276	81	229	21	24	13	12	86
TzMagubike2 SE5_r01	170	13	13	5	149	69	5770	11	16	276	79	228	16	23	13	12	75
TzMagubike2 SE5_r02	201	12	12	5	143	70	5849	11	20	269	80	185	17	24	13	12	72
Average	180	13	15	5	149	69	5817	12	19	274	80	214	18	24	13	12	78

Appendix 8.8: Full results of the SEM-EDS chemical composition (in wt%) of fayalite and monticellite in the smelting slags from Kalenga. Note the results are the average of three spectra and are normalised to 100 wt%

Sample	Spectrum	Na2O	MgO	Al2O3	SiO2	P2O5	K2O	CaO	MnO	FeO	ZrO2	Total
TzNgongwa SE5	Spectrum 1	0.0	1.1	0.4	30.1	0.0	0.0	0.5	0.5	66.6	0.8	100
	Spectrum 2	0.0	1.4	0.3	30.4	0.1	0.0	0.5	0.3	66.4	0.5	100
	Spectrum 3	0.0	1.2	0.3	30.4	0.0	0.1	0.5	0.3	66.4	0.7	100
	Mean	0.0	1.2	0.3	30.3	0.0	0.1	0.5	0.4	66.5	0.7	100
TzNgongwa SE6	Spectrum 1	0.0	2.0	0.1	30.3	0.0	0.0	0.2	0.4	66.9	0.1	100
	Spectrum 2	0.1	1.7	0.1	30.5	0.1	0.0	0.4	0.3	66.9	0.1	100
	Spectrum 3	0.1	1.7	0.1	30.2	0.0	0.0	0.2	0.4	67.0	0.3	100
	Mean	0.1	1.8	0.1	30.3	0.0	0.0	0.2	0.4	66.9	0.2	100
TzNgongwa SE7	Spectrum 1	0.0	1.2	0.2	30.5	0.0	0.0	0.4	0.6	66.5	0.6	100
	Spectrum 2	0.1	1.4	0.5	29.8	0.0	0.0	0.4	0.4	66.4	0.9	100
	Spectrum 3	0.1	1.1	0.3	30.3	0.0	0.0	0.5	0.3	66.9	0.4	100
	Mean	0.1	1.2	0.3	30.2	0.0	0.0	0.5	0.4	66.6	0.7	100
S1-Ngon-EA1	Spectrum 1	0.0	1.4	0.0	30.7	0.2	0.1	0.3	0.3	67.2	-0.2	100
	Spectrum 2	0.1	1.2	0.2	30.7	0.1	0.0	0.2	0.4	67.3	-0.2	100
	Spectrum 3	-0.1	1.8	0.2	30.6	-0.1	0.0	0.4	0.3	67.1	-0.1	100
	Mean	0.0	1.5	0.1	30.6	0.1	0.1	0.3	0.3	67.2	-0.2	100
S1-Ngon-SA1	Spectrum 1	0.1	0.5	0.1	30.2	0.1	0.0	0.4	0.5	68.1	-0.2	100
	Spectrum 2	0.1	0.7	0.2	30.1	-0.1	-0.1	0.5	0.3	67.6	0.5	100
	Spectrum 3	0.0	0.8	0.2	30.3	0.0	0.0	0.4	0.3	68.0	0.0	100
	Mean	0.1	0.7	0.2	30.2	0.0	0.0	0.5	0.4	67.9	0.1	100
TzMagubike1-1 SE1	Spectrum 1	0.2	1.1	0.2	33.0	0.8	0.1	20.5	-0.1	44.6	-0.3	100
	Spectrum 2	0.1	1.2	0.6	32.5	0.7	0.4	23.8	-0.1	40.5	0.2	100
	Spectrum 3	0.0	1.5	1.1	32.5	0.5	0.5	23.4	0.3	40.3	-0.2	100
	Mean	0.1	1.3	0.7	32.7	0.7	0.4	22.6	0.0	41.8	-0.1	100
TzMagubike1-2 SE2	Spectrum 1	0.0	4.5	-0.1	33.7	1.0	-0.1	33.7	0.2	27.4	-0.3	100
	Spectrum 2	0.1	3.7	-0.1	34.3	0.0	0.0	33.5	0.0	28.6	-0.2	100
	Spectrum 3	0.1	3.4	-0.1	34.3	0.3	0.0	33.2	0.1	28.6	0.1	100
	Mean	0.1	3.9	-0.1	34.1	0.4	0.0	33.5	0.1	28.2	-0.1	100
TzMagubike1-2 SE3	Spectrum 1	0.1	1.7	0.4	33.1	0.6	0.5	24.7	0.2	38.6	0.2	100
	Spectrum 2	0.2	1.5	0.8	33.1	0.5	0.7	23.5	0.3	38.1	1.4	100
	Spectrum 3	0.1	2.1	0.7	34.0	0.5	0.7	22.9	0.3	38.7	0.1	100
	Mean	0.1	1.8	0.6	33.4	0.5	0.6	23.7	0.3	38.5	0.6	100
TzMagubike1-3 SE4	Spectrum 1	0.7	0.6	5.6	34.6	0.7	2.4	30.8	0.0	24.7	-0.1	100
	Spectrum 2	1.2	0.5	6.0	34.8	0.6	1.8	30.9	0.1	24.3	-0.3	100
	Spectrum 3	0.4	0.6	4.5	34.1	0.7	2.3	31.9	0.0	25.6	-0.1	100
	Mean	0.8	0.5	5.4	34.5	0.7	2.2	31.2	0.0	24.9	-0.1	100
TzMagubike1-4 SE5	Spectrum 1	0.1	1.6	0.1	31.3	0.4	0.0	0.7	0.1	65.8	-0.3	100
	Spectrum 2	0.0	1.2	0.1	31.2	0.0	0.0	0.9	0.2	66.5	-0.1	100
	Spectrum 3	0.1	1.5	-0.1	31.7	0.5	-0.1	0.7	0.0	66.2	-0.5	100
	Mean	0.1	1.5	0.1	31.4	0.3	0.0	0.8	0.1	66.2	-0.3	100
TzMagubike2 SE1	Spectrum 1	0.0	0.8	0.4	30.9	0.2	-0.1	0.5	0.1	66.9	0.3	100
	Spectrum 2	0.0	0.8	0.2	31.0	0.4	0.1	0.5	0.0	66.8	0.1	100
	Spectrum 3	-0.1	1.0	0.3	30.2	0.4	0.0	0.5	0.1	67.0	0.6	100
	Mean	0.0	0.8	0.3	30.7	0.4	0.0	0.5	0.1	66.9	0.3	100
TzMagubike2 SE2	Spectrum 1	0.1	0.9	0.2	30.3	0.0	0.0	0.3	0.1	67.6	0.5	100
	Spectrum 2	0.0	0.7	0.3	30.9	-0.1	0.1	0.4	0.2	67.4	0.1	100
	Spectrum 3	0.1	0.7	0.2	30.9	0.0	0.0	0.3	-0.1	67.5	0.3	100
	Mean	0.1	0.8	0.2	30.7	0.0	0.0	0.3	0.1	67.5	0.3	100
TzMagubike2 SE3	Spectrum 1	0.1	0.9	0.2	30.9	0.2	0.0	0.2	0.3	67.2	0.0	100
	Spectrum 2	0.1	1.0	0.4	30.5	0.0	0.0	0.3	0.1	67.0	0.6	100
	Spectrum 3	0.0	0.5	0.7	30.5	0.1	0.3	0.5	0.3	65.7	1.3	100
	Mean	0.1	0.8	0.4	30.6	0.1	0.1	0.4	0.2	66.6	0.6	100

TzMagubike2 SE4	Spectrum 1	-0.1	0.9	0.2	30.4	0.2	0.1	0.4	0.2	67.9	-0.2	100
	Spectrum 2	0.1	0.8	0.0	30.2	-0.2	0.0	0.4	0.1	68.1	0.4	100
	Spectrum 3	-0.1	0.9	0.1	30.3	0.1	0.0	0.4	0.2	68.1	0.0	100
	Mean	0.0	0.9	0.1	30.3	0.1	0.0	0.4	0.2	68.1	0.0	100
TzMagubike2 SE5	Spectrum 1	-0.1	1.1	0.0	30.5	0.1	0.0	0.4	0.1	67.8	0.0	100
	Spectrum 2	-0.1	0.6	0.2	30.6	-0.2	0.1	0.5	0.2	67.6	0.6	100
	Spectrum 3	0.2	0.9	0.2	30.2	0.2	0.2	0.4	0.2	67.1	0.4	100
	Mean	0.0	0.9	0.1	30.4	0.0	0.1	0.4	0.2	67.5	0.3	100

Appendix 9: Chapter 9 Appendices

Appendix 9.1: List of smelting (SE) and smithing (ST) sites from Njombe administrative ward. Note DWS=distance to nearest water source

S/No.	Site	GPS Location	DWS (m)	Area (m^2)	Elevation (m)	Discovered by
1	Msete SE1	S (9^0 22.316'), E (34^0 50.001')	13	28	1780	John A. Fute
2	Msete SE2	S (9^0 22.358'), E (34^0 49.875')	40	13	1785	Edwinus Lyaya
3	Mjimwema SE1	S (9^0 22.175'), E (34^0 50.033')	50	15	1800	Edwinus Lyaya
4	Nundu ST1	S (9^0 22.441'), E (34^0 50.013')	155	79	1840	John A. Fute
5	Nundu SE2	S (9^0 22.400'), E (34^0 49.939')	48	15	1812	John A. Fute
6	Nundu SE3	S (9^0 22.395'), E (34^0 49.982')	88	15	1822	John A. Fute
7	**Average**		**66**	**28**	**1807**	

Appendix 9.2: Full results of the (P) XRF-EDS major and minor oxide concentrations (in wt%) of the technical ceramics from Msete and Nundu sites. Note the results are not normalised to 100 wt%, TYR=tuyère, FW=furnace wall, and PTR=pottery

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	AT
TzMsete1 TYR1	1.32	0.71	28.04	69.21	0.04	0.03	1.38	0.13	0.65	0.01	0.02	0.01	1.34	103
TzMsete1 TYR1_r01	0.60	0.74	28.28	69.60	0.04	0.03	1.41	0.13	0.66	0.01	0.02	0.01	1.35	103
TzMsete1 TYR1_r02	1.21	0.73	28.25	69.09	0.04	0.03	1.38	0.13	0.66	0.01	0.02	0.01	1.34	103
Average	1.04	0.73	28.19	69.30	0.04	0.03	1.39	0.13	0.66	0.01	0.02	0.01	1.34	103
TzMsete1 TYR2	0.87	0.90	33.84	62.71	0.07	0.03	1.18	0.06	0.74	0.01	0.01	0.02	2.48	103
TzMsete1 TYR2_r01	0.61	0.87	33.97	62.82	0.09	0.04	1.18	0.06	0.76	0.01	0.01	0.02	2.50	103
TzMsete1 TYR2_r02	0.71	0.88	33.88	62.81	0.06	0.04	1.18	0.06	0.76	0.01	0.01	0.02	2.50	103
Average	0.73	0.88	33.90	62.78	0.07	0.04	1.18	0.06	0.75	0.01	0.01	0.02	2.49	103
TzMsete1 TYR3	1.12	0.80	29.76	67.03	0.04	0.02	1.59	0.18	0.64	0.01	0.02	0.02	1.69	103
TzMsete1 TYR3_r01	1.26	0.88	29.71	66.86	0.04	0.03	1.60	0.17	0.64	0.01	0.02	0.01	1.69	103
TzMsete1 TYR3_r02	1.14	0.82	29.75	66.98	0.04	0.02	1.61	0.18	0.63	0.01	0.02	0.02	1.69	103
Average	1.17	0.83	29.74	66.96	0.04	0.02	1.60	0.18	0.64	0.01	0.02	0.01	1.69	103
TzMsete2 FW1	1.11	0.51	26.50	69.79	0.04	0.04	2.84	0.01	0.34	0.00	0.01	0.02	1.75	103
TzMsete2 FW1_r01	0.82	0.57	26.59	69.82	0.05	0.04	2.89	0.03	0.34	0.01	0.01	0.02	1.76	103
TzMsete2 FW1_r02	1.11	0.53	26.45	69.79	0.04	0.04	2.84	0.03	0.34	0.00	0.01	0.02	1.75	103
Average	1.01	0.54	26.51	69.80	0.04	0.04	2.85	0.02	0.34	0.00	0.01	0.02	1.75	103
TzMsete2 FW2	0.78	0.61	27.91	68.36	0.06	0.04	2.81	0.04	0.40	0.01	0.01	0.02	1.91	103

TzMsete2 FW2_r01	0.97	0.58	27.97	68.17	0.04	0.04	2.81	0.03	0.40	0.01	0.01	0.02	1.90	103
TzMsete2 FW2_r02	0.74	0.61	27.87	68.43	0.06	0.04	2.82	0.03	0.40	0.01	0.01	0.02	1.90	103
Average	0.83	0.60	27.92	68.32	0.05	0.04	2.82	0.03	0.40	0.01	0.01	0.02	1.90	103
TzMsete2 FW3	0.73	0.60	28.36	68.15	0.06	0.04	2.81	0.03	0.35	0.01	0.01	0.02	1.79	103
TzMsete2 FW3_r01	0.76	0.65	28.33	68.13	0.05	0.04	2.80	0.03	0.34	0.01	0.01	0.02	1.77	103
TzMsete2 FW3_r02	0.86	0.58	28.27	68.18	0.06	0.04	2.81	0.01	0.35	0.01	0.01	0.02	1.77	103
Average	0.78	0.61	28.32	68.15	0.06	0.04	2.81	0.02	0.35	0.01	0.01	0.02	1.78	103
TzMsete2 PTR1	1.01	1.24	30.02	64.59	0.31	0.06	2.50	0.36	0.74	0.01	0.01	0.01	2.03	103
TzMsete2 PTR1_r01	0.94	1.25	30.06	64.63	0.30	0.07	2.50	0.35	0.75	0.01	0.01	0.01	2.03	103
TzMsete2 PTR1_r02	1.23	1.30	30.00	64.34	0.31	0.06	2.49	0.36	0.73	0.02	0.01	0.01	2.04	103
Average	1.06	1.26	30.03	64.52	0.31	0.06	2.50	0.36	0.74	0.02	0.01	0.01	2.03	103
TzMsete2 PTR2	1.29	1.33	30.98	63.24	0.31	0.07	2.52	0.36	0.75	0.02	0.01	0.01	2.03	103
TzMsete2 PTR2_r01	1.00	1.44	31.07	63.29	0.32	0.07	2.52	0.37	0.75	0.02	0.01	0.01	2.05	103
TzMsete2 PTR2_r02	1.13	1.32	31.15	63.20	0.31	0.07	2.53	0.36	0.76	0.01	0.01	0.01	2.05	103
Average	1.14	1.36	31.07	63.24	0.31	0.07	2.52	0.36	0.75	0.02	0.01	0.01	2.05	103
TzMsete2 PTR3	0.95	1.29	30.98	63.52	0.32	0.07	2.55	0.37	0.76	0.02	0.02	0.02	2.07	103
TzMsete2 PTR3_r01	1.14	1.31	30.90	63.41	0.31	0.07	2.56	0.35	0.76	0.01	0.01	0.01	2.06	103
TzMsete2 PTR3_r02	0.62	1.33	30.95	63.81	0.32	0.07	2.56	0.37	0.76	0.01	0.02	0.01	2.08	103
Average	0.90	1.31	30.94	63.58	0.32	0.07	2.55	0.36	0.76	0.01	0.02	0.01	2.07	103
TzMsete2 S1	1.12	0.53	33.60	64.61	0.03	0.03	1.37	0.07	0.45	0.01	0.01	0.01	1.11	103
TzMsete2 S1_r01	0.89	0.55	33.71	64.70	0.03	0.03	1.37	0.07	0.45	0.01	0.01	0.01	1.12	103
TzMsete2 S1_r02	0.84	0.60	33.53	64.86	0.03	0.03	1.37	0.07	0.45	0.01	0.01	0.01	1.13	103
Average	0.95	0.56	33.61	64.72	0.03	0.03	1.37	0.07	0.45	0.01	0.01	0.01	1.12	103
TzMsete2 S2	0.75	0.57	30.42	68.14	0.03	0.02	1.43	0.07	0.42	0.01	0.01	0.01	1.04	103
TzMsete2 S2_r01	1.03	0.54	30.34	67.98	0.03	0.02	1.41	0.08	0.42	0.01	0.01	0.01	1.05	103
TzMsete2 S2_r02	0.91	0.62	30.27	68.11	0.03	0.02	1.40	0.07	0.42	0.00	0.01	0.01	1.04	103
Average	0.90	0.57	30.34	68.08	0.03	0.02	1.41	0.07	0.42	0.01	0.01	0.01	1.05	103
TzMsete2 TYR3	0.87	0.66	30.30	67.17	0.04	0.02	1.61	0.15	0.70	0.01	0.02	0.01	1.35	103
TzMsete2 TYR3_r01	1.31	0.68	30.32	66.76	0.03	0.02	1.59	0.15	0.68	0.01	0.02	0.01	1.34	103
TzMsete2 TYR3_r02	0.65	0.75	30.38	67.22	0.04	0.02	1.61	0.15	0.70	0.01	0.02	0.01	1.36	103
Average	0.94	0.69	30.33	67.05	0.04	0.02	1.60	0.15	0.69	0.01	0.02	0.01	1.35	103
TzNundu1 PTR1	1.15	1.81	30.27	63.42	0.15	0.03	1.33	0.47	1.16	0.03	0.04	0.02	3.03	103
TzNundu1 PTR1_r01	1.21	1.88	30.18	63.39	0.15	0.04	1.33	0.46	1.16	0.03	0.04	0.02	3.04	103
TzNundu1 PTR1_r02	1.16	1.80	30.19	63.53	0.15	0.04	1.30	0.47	1.15	0.04	0.03	0.02	3.03	103
Average	1.17	1.83	30.21	63.45	0.15	0.04	1.32	0.47	1.16	0.03	0.04	0.02	3.03	103
TzNundu1 PTR2	0.83	1.36	26.99	67.42	0.13	0.03	1.25	0.50	0.74	0.02	0.04	0.02	3.61	103
TzNundu1 PTR2_r01	0.73	1.33	27.10	67.35	0.14	0.03	1.30	0.51	0.74	0.02	0.04	0.02	3.63	103
TzNundu1 PTR2_r02	0.80	1.23	27.30	67.26	0.13	0.03	1.25	0.52	0.74	0.02	0.04	0.02	3.60	103
Average	0.79	1.31	27.13	67.34	0.13	0.03	1.26	0.51	0.74	0.02	0.04	0.02	3.62	103
TzNundu1 PTR3	1.22	1.39	24.79	69.73	0.09	0.02	1.14	0.48	0.66	0.01	0.03	0.02	3.34	103
TzNundu1 PTR3_r01	0.84	1.32	24.75	70.15	0.09	0.02	1.16	0.49	0.66	0.02	0.03	0.02	3.38	103
TzNundu1 PTR3_r02	0.82	1.36	24.88	70.04	0.10	0.02	1.14	0.46	0.66	0.02	0.03	0.02	3.37	103
Average	0.96	1.36	24.81	69.97	0.09	0.02	1.15	0.48	0.66	0.02	0.03	0.02	3.37	103
TzNundu1 TYR1	0.95	0.60	34.07	63.46	0.04	0.03	1.49	0.18	0.82	0.01	0.01	0.01	1.25	103
TzNundu1 TYR1_r01	0.93	0.51	34.06	63.55	0.06	0.04	1.51	0.18	0.82	0.01	0.01	0.01	1.25	103
TzNundu1 TYR1_r02	1.37	0.54	33.92	63.27	0.04	0.04	1.47	0.19	0.81	0.01	0.01	0.01	1.25	103

Average	1.08	0.55	34.02	63.43	0.04	0.04	1.49	0.19	0.82	0.01	0.01	0.01	1.25	103
TzNundu1 TYR2	0.99	0.81	32.83	65.03	0.03	0.02	1.75	0.08	0.43	0.00	0.02	0.01	0.93	103
TzNundu1 TYR2_r01	0.72	0.74	32.88	65.32	0.03	0.02	1.75	0.07	0.43	0.00	0.02	0.01	0.93	103
TzNundu1 TYR2_r02	0.73	0.79	32.84	65.28	0.04	0.03	1.75	0.07	0.44	0.00	0.02	0.01	0.92	103
Average	0.81	0.78	32.85	65.21	0.03	0.02	1.75	0.07	0.43	0.00	0.02	0.01	0.93	103
TzNundu1 TYR3	0.97	0.98	34.51	62.12	0.03	0.03	2.56	0.11	0.49	0.01	0.02	0.01	1.07	103
TzNundu1 TYR3_r01	0.91	0.97	34.57	62.10	0.03	0.03	2.57	0.12	0.50	0.00	0.02	0.01	1.08	103
TzNundu1 TYR3_r02	0.56	1.02	34.57	62.35	0.03	0.04	2.61	0.11	0.50	0.01	0.02	0.01	1.08	103
Average	0.81	0.99	34.55	62.19	0.03	0.04	2.58	0.12	0.50	0.01	0.02	0.01	1.07	103

Appendix 9.3: Full results of the (P) XRF-EDS trace element concentrations (in ppm) of the technical ceramics from Msete and Nundu sites. Note the results are not normalised to 100 wt%, TYR=tuyère, FW=furnace wall, and PTR=pottery

Sample	Co3O4	NiO	CuO	ZnO	Ga	Rb2O	SrO	Y	ZrO2	Nb2O5	Ba	La	Ce	Hf	WO3	PbO	Th
TzMsete1 TYR1	29	16	34	50	14	56	29	13	220	37	187	7	17	12	300	17	16
TzMsete1 TYR1_r01	36	12	37	51	14	57	30	13	224	36	190	8	25	11	298	17	17
TzMsete1 TYR1_r02	48	12	36	49	14	56	29	13	217	34	187	7	22	10	288	17	17
Average	37	13	36	50	14	56	30	13	220	35	188	7	21	11	296	17	17
TzMsete1 TYR2	36	10	55	55	16	71	19	22	200	32	117	22	45	10	51	19	23
TzMsete1 TYR2_r01	34	9	57	55	15	71	19	22	198	36	117	23	46	8	52	20	24
TzMsete1 TYR2_r02	26	7	52	58	15	71	19	21	204	36	118	24	47	12	48	20	23
Average	32	8	54	56	15	71	19	22	200	35	117	23	46	10	50	19	23
TzMsete1 TYR3	31	8	32	41	12	58	34	17	183	30	180	13	37	12	158	17	17
TzMsete1 TYR3_r01	26	9	32	41	13	58	34	16	180	28	181	13	37	12	150	18	17
TzMsete1 TYR3_r02	34	13	35	40	13	59	35	16	177	30	179	12	38	8	158	17	17
Average	30	10	33	41	13	58	34	16	180	29	180	13	37	10	155	17	17
TzMsete2 FW1	20	3	19	19	11	79	13	17	105	12	182	13	26	6	38	9	15
TzMsete2 FW1_r01	30	2	19	17	10	79	13	16	106	12	185	13	26	6	39	9	16
TzMsete2 FW1_r02	20	7	18	20	11	78	13	16	104	12	184	14	27	8	42	9	14
Average	23	4	19	18	11	79	13	17	105	12	183	13	26	7	40	9	15
TzMsete2 FW2	27	7	30	22	12	79	13	15	93	13	179	15	15	6	42	9	13
TzMsete2 FW2_r01	31	3	32	20	12	79	13	15	99	15	174	11	17	8	38	10	12
TzMsete2 FW2_r02	32	3	29	20	12	79	13	15	97	12	175	12	16	7	38	10	13
Average	30	4	30	20	12	79	13	15	97	13	176	13	16	7	39	9	13
TzMsete2 FW3	27	4	22	18	12	80	13	16	96	13	170	14	28	5	38	9	13
TzMsete2 FW3_r01	31	2	19	19	11	80	13	16	102	10	173	14	17	7	36	9	14
TzMsete2 FW3_r02	18	6	20	18	11	79	13	16	100	11	174	13	18	7	45	9	13
Average	25	4	20	19	11	79	13	16	99	11	172	14	21	6	40	9	13
TzMsete2 PTR1	29	22	48	44	13	85	57	16	112	18	287	13	31	8	58	15	10
TzMsete2 PTR1_r01	40	19	45	42	12	85	58	16	115	15	285	12	30	7	55	15	11
TzMsete2 PTR1_r02	33	21	46	42	13	84	57	16	119	15	284	13	31	6	57	16	11
Average	34	21	46	43	13	85	57	16	115	16	285	12	30	7	57	15	11
TzMsete2 PTR2	24	26	49	43	14	84	57	17	111	17	283	11	27	6	45	16	11
TzMsete2 PTR2_r01	21	24	47	43	13	85	57	16	108	15	286	14	31	9	44	15	11
TzMsete2 PTR2_r02	30	24	50	42	14	86	58	17	112	16	284	10	31	7	41	15	11
Average	25	25	49	42	14	85	57	17	111	16	284	12	30	7	43	15	11
TzMsete2 PTR3	35	20	50	44	14	85	58	17	110	17	290	13	31	8	37	15	11

TzMsete2 PTR3_r01	23	21	49	43	13	85	58	17	111	17	285	11	25	9	42	15	10
TzMsete2 PTR3_r02	37	24	53	46	14	86	59	17	113	17	288	11	31	6	42	15	11
Average	31	22	51	44	14	86	58	17	111	17	288	11	29	8	40	15	11
TzMsete2 S1	28	15	22	56	16	55	9	18	117	24	91	12	27	8	39	13	24
TzMsete2 S1_r01	14	15	22	56	16	56	9	18	120	26	93	13	31	10	39	12	22
TzMsete2 S1_r02	17	15	24	55	16	55	10	18	118	27	92	11	25	8	41	12	23
Average	20	15	23	56	16	55	9	18	118	25	92	12	28	9	40	12	23
TzMsete2 S2	45	18	26	37	17	58	10	19	113	25	88	20	37	10	237	12	21
TzMsete2 S2_r01	44	16	27	38	16	57	10	19	114	23	83	15	37	9	243	13	20
TzMsete2 S2_r02	47	17	26	37	17	56	10	19	115	25	86	17	42	8	241	13	20
Average	45	17	26	37	16	57	10	19	114	24	86	18	39	9	240	13	20
TzMsete2 TYR3	39	15	28	44	15	62	31	10	141	28	210	8	10	8	269	13	12
TzMsete2 TYR3_r01	23	17	26	40	15	62	31	10	144	26	207	9	15	8	266	13	12
TzMsete2 TYR3_r02	37	16	25	42	14	63	32	10	143	29	212	8	14	9	270	13	11
Average	33	16	26	42	14	62	31	10	143	27	209	8	13	8	268	13	12
TzNundu1 PTR1	50	48	48	37	15	57	58	18	132	12	152	13	19	5	103	9	6
TzNundu1 PTR1_r01	45	50	46	37	14	57	58	19	136	18	154	16	33	7	104	9	6
TzNundu1 PTR1_r02	59	44	47	36	15	56	58	18	131	13	152	10	31	7	104	9	6
Average	51	47	47	37	15	56	58	18	133	14	153	13	28	6	104	9	6
TzNundu1 PTR2	52	65	86	39	12	56	20	16	113	13	104	14	29	8	89	17	14
TzNundu1 PTR2_r01	54	58	85	34	10	56	21	16	110	13	103	15	33	5	84	17	13
TzNundu1 PTR2_r02	54	64	90	38	11	57	20	16	116	12	103	11	28	7	95	16	13
Average	54	62	87	37	11	56	20	16	113	13	103	13	30	7	89	17	13
TzNundu1 PTR3	47	58	74	35	10	54	18	15	100	12	106	16	32	5	102	16	13
TzNundu1 PTR3_r01	57	54	74	32	10	55	19	16	104	11	105	13	23	6	104	15	13
TzNundu1 PTR3_r02	61	58	73	34	11	55	19	16	97	9	105	13	22	7	100	16	13
Average	55	57	74	34	10	55	19	16	100	11	106	14	26	6	102	16	13
TzNundu1 TYR1	22	16	20	43	16	56	40	9	153	30	195	7	8	6	75	13	12
TzNundu1 TYR1_r01	38	16	20	40	15	57	40	10	152	30	197	7	9	7	80	14	13
TzNundu1 TYR1_r02	32	14	20	42	16	56	40	9	150	31	193	6	11	6	77	13	13
Average	31	15	20	41	16	56	40	9	151	30	195	7	9	6	77	13	13
TzNundu1 TYR2	32	16	27	35	15	67	10	20	114	22	68	14	32	8	276	11	20
TzNundu1 TYR2_r01	37	16	25	36	16	67	10	19	106	23	69	13	28	9	273	11	20
TzNundu1 TYR2_r02	41	15	29	32	15	67	10	19	108	24	71	14	32	6	269	11	20
Average	37	16	27	34	15	67	10	19	109	23	69	14	31	8	273	11	20
TzNundu1 TYR3	26	17	31	36	17	93	14	22	142	28	102	16	39	10	198	14	23
TzNundu1 TYR3_r01	34	18	30	38	18	93	14	23	138	30	105	18	38	10	200	14	25
TzNundu1 TYR3_r02	28	21	27	39	18	94	14	23	141	27	103	16	41	10	195	14	25
Average	30	19	29	38	18	93	14	23	140	28	103	17	39	10	198	14	24

Appendix 9.4: Full results of the SEM-EDS bulk area composition of the major and minor oxides of the smelting slags from Msete 1, and Nundu 2 sites. Note the results are normalised to 100 wt%

Sample	Area	MgO	Al2O3	SiO2	K2O	CaO	TiO2	V2O5	MnO	FeO	Total
Nundu SE6	Area 1	0.6	5.5	23.0	1.3	1.5	3.5	0.2	0.3	64.0	100
	Area 2	0.7	5.8	23.0	1.4	1.6	3.5	0.3	0.4	63.4	100
	Area 3	0.6	5.4	22.4	1.3	1.5	3.5	0.5	0.4	64.3	100
	Mean	0.6	5.6	22.8	1.3	1.5	3.5	0.3	0.4	63.9	100
Nundu SE7	Area 1	0.7	5.2	25.5	1.0	1.8	5.0	0.4	0.2	60.1	100
	Area 2	0.6	5.0	24.8	1.0	1.8	5.6	0.5	0.4	60.3	100
	Area 3	0.6	5.1	24.2	0.9	1.8	6.0	0.5	0.4	60.5	100
	Mean	0.6	5.1	24.8	1.0	1.8	5.5	0.5	0.4	60.3	100
Nundu SE8	Area 1	1.0	6.6	22.3	1.3	2.1	6.6	0.6	0.3	59.1	100
	Area 2	0.8	6.8	22.0	1.4	2.2	6.5	0.5	0.4	59.4	100
	Area 3	0.9	6.6	22.2	1.4	2.3	6.7	0.5	0.4	58.9	100
	Mean	0.9	6.6	22.2	1.4	2.2	6.6	0.5	0.4	59.2	100
Nundu SE9	Area 1	0.7	11.0	25.5	2.4	1.8	7.0	0.7	0.2	50.6	100
	Area 2	0.6	10.7	25.4	2.3	2.1	7.5	0.9	0.4	50.1	100
	Area 3	0.7	10.7	26.4	2.7	1.7	6.7	0.5	0.4	50.3	100
	Mean	0.7	10.8	25.8	2.4	1.9	7.1	0.7	0.3	50.3	100
Nundu SE10	Area 1	0.7	5.9	24.2	1.1	2.2	4.7	0.4	0.3	60.4	100
	Area 2	0.6	5.8	23.6	1.4	2.1	5.1	0.6	0.4	60.4	100
	Area 3	0.6	5.9	24.8	1.4	2.3	4.1	0.2	0.4	60.2	100
	Mean	0.7	5.9	24.2	1.3	2.2	4.6	0.4	0.4	60.3	100
Msete1 SE1	Area 1	0.7	5.4	19.5	0.9	1.7	5.7	0.5	0.3	65.3	100
	Area 2	0.6	5.6	18.6	0.9	1.8	6.5	0.6	0.5	64.9	100
	Area 3	0.5	5.3	19.0	0.9	1.7	6.2	0.6	0.5	65.4	100
	Mean	0.6	5.5	19.1	0.9	1.7	6.1	0.5	0.4	65.2	100
Msete1 SE2	Area 1	0.6	5.9	26.8	1.2	1.8	3.7	0.2	0.3	59.5	100
	Area 2	0.7	5.2	26.6	1.2	1.7	3.7	0.1	0.3	60.5	100
	Area 3	0.5	5.5	26.6	1.1	1.8	3.7	0.3	0.3	60.2	100
	Mean	0.6	5.5	26.7	1.2	1.7	3.7	0.2	0.3	60.0	100
Msete1 SE3	Area 1	0.5	6.2	25.0	1.4	2.9	5.3	0.6	0.4	57.8	100
	Area 2	0.6	5.9	25.2	1.4	2.9	5.0	0.4	0.5	58.1	100
	Area 3	0.5	5.9	25.5	1.5	2.8	5.3	0.6	0.3	57.6	100
	Mean	0.6	6.0	25.2	1.4	2.8	5.2	0.5	0.4	57.8	100
Msete1 SE4	Area 1	0.6	5.4	23.4	1.2	3.5	6.5	0.7	0.3	58.5	100
	Area 2	0.5	4.1	41.7	0.9	2.7	4.6	0.4	0.4	44.7	100
	Area 3	0.7	5.9	23.0	1.1	3.4	6.6	0.7	0.3	58.3	100
	Mean	0.6	5.1	29.4	1.1	3.2	5.9	0.6	0.4	53.8	100
Msete1 SE5	Area 1	0.7	5.9	24.4	1.6	2.8	3.9	0.3	0.3	60.2	100
	Area 2	0.9	5.8	24.7	1.5	2.7	4.0	0.2	0.5	59.7	100
	Area 3	0.6	5.8	24.6	1.6	2.8	3.9	0.2	0.4	60.2	100
	Mean	0.8	5.8	24.5	1.6	2.7	3.9	0.2	0.4	60.0	100

Appendix 9.5: Full results of the (P) XRF-EDS trace oxide concentrations (in ppm) of the smelting from Msete 1, and Nundu 2 sites. Note the results are not normalised to 100 wt%

Sample	Co3O4	NiO	CuO	ZnO	Ga	SrO	Y	ZrO2	Nb2O5	Ba	Ce	Hf	Ta2O5	WO3	Th	U
TzMsete1 SE1	160	11	70	15	23	102	12	69	8	88	18	16	26	19	14	11
TzMsete1 SE1_r01	160	11	81	6	30	103	11	49	13	83	17	17	19	17	14	10
TzMsete1 SE1_r02	196	11	79	5	31	105	13	64	9	88	16	17	19	19	14	23
Average	172	11	77	8	28	103	12	61	10	86	17	17	21	18	14	15
TzMsete1 SE2	150	10	76	13	27	87	12	70	12	73	12	15	18	16	13	19
TzMsete1 SE2_r01	132	10	83	21	28	83	13	77	13	69	18	16	18	16	13	13
TzMsete1 SE2_r02	299	10	82	12	20	90	11	73	14	74	18	17	19	16	13	11
Average	194	10	80	15	25	87	12	73	13	72	16	16	18	16	13	14
TzMsete1 SE3	150	10	62	4	16	149	14	60	16	94	19	16	17	17	12	11
TzMsete1 SE3_r01	150	10	68	4	21	146	15	65	17	97	13	15	17	16	12	10
TzMsete1 SE3_r02	150	9	57	4	15	148	12	64	6	99	16	14	17	17	12	17
Average	150	10	62	4	18	148	14	63	13	97	16	15	17	17	12	13
TzMsete1 SE4	150	10	68	4	28	208	14	83	18	93	22	15	16	16	12	12
TzMsete1 SE4_r01	150	10	71	8	32	204	15	65	18	92	20	14	17	15	12	9
TzMsete1 SE4_r02	150	10	38	4	19	205	14	66	11	92	25	15	29	15	12	11
Average	150	10	59	5	26	206	14	71	15	92	22	15	21	15	12	11
TzMsete1 SE5	150	9	61	4	17	146	13	63	24	108	24	15	17	17	13	11
TzMsete1 SE5_r01	150	10	65	4	18	148	13	62	12	120	24	15	18	16	13	12
TzMsete1 SE5_r02	150	9	55	4	17	149	13	65	11	113	13	14	19	15	13	20
Average	150	9	60	4	17	147	13	63	16	114	21	15	18	16	13	14
TzMsete2 SE10	150	10	68	5	18	113	12	88	22	71	17	15	19	19	12	10
TzMsete2 SE10_r01	150	10	76	9	26	114	14	86	10	75	13	16	17	17	13	11
TzMsete2 SE10_r02	150	10	66	7	18	113	13	79	15	72	19	15	23	59	12	11
Average	150	10	70	7	20	113	13	84	16	72	16	15	20	32	12	11
TzMsete2 SE6	177	10	86	19	21	100	13	77	16	81	14	17	20	16	13	11
TzMsete2 SE6_r01	150	11	76	23	16	104	14	68	15	86	15	17	32	16	13	11
TzMsete2 SE6_r02	150	10	66	14	20	99	13	66	11	81	17	16	19	16	13	7
Average	159	10	76	19	19	101	13	70	14	82	15	17	24	16	13	10
TzMsete2 SE7	150	9	75	23	19	114	13	59	7	90	19	16	29	19	12	9
TzMsete2 SE7_r01	150	10	58	14	16	110	11	65	8	95	13	17	28	19	13	17
TzMsete2 SE7_r02	150	11	56	10	19	113	12	64	8	92	16	17	24	19	12	12
Average	150	10	63	16	18	112	12	63	8	93	16	17	27	19	12	13
TzMsete2 SE8	150	10	45	4	24	156	13	72	9	134	13	15	16	19	12	11
TzMsete2 SE8_r01	150	11	67	10	26	152	13	78	17	139	12	14	16	18	12	11
TzMsete2 SE8_r02	150	9	57	4	22	148	13	71	10	134	12	14	17	79	12	12
Average	150	10	56	6	24	152	13	73	12	135	12	14	16	39	12	12
TzMsete2 SE9	130	8	112	18	25	88	15	45	8	133	15	16	19	15	9	12
TzMsete2 SE9_r01	130	8	109	15	20	89	14	47	10	144	13	16	19	15	9	8
TzMsete2 SE9_r02	135	8	111	15	17	89	14	44	11	139	14	16	19	16	9	14
Average	132	8	111	16	21	89	14	45	10	138	14	16	19	15	9	12

Appendix 9.6: Full results of the SEM-EDS chemical composition of fayalite from the Msete 1 and Nundu 2 sites. Note the results are the average of three spectra and are normalised to 100 wt%

Sample	Spectrum	MgO	Al2O3	SiO2	CaO	TiO2	MnO	FeO	Total
Msete1 SE1	Spectrum 1	1.6	0.5	30.3	0.7	0.8	0.7	65.3	100
	Spectrum 2	1.2	0.3	30.8	0.7	0.6	0.6	65.8	100
	Spectrum 3	1.2	0.3	30.6	0.9	0.8	0.6	65.7	100
	Mean	1.3	0.3	30.6	0.8	0.7	0.7	65.6	100
Msete1 SE2	Spectrum 1	1.3	0.2	31.1	0.3	0.5	0.4	66.1	100
	Spectrum 2	0.9	0.3	30.9	0.4	0.8	0.5	66.2	100
	Spectrum 3	1.0	0.2	30.7	0.6	0.6	0.4	66.5	100
	Mean	1.1	0.3	30.9	0.4	0.6	0.4	66.3	100
Msete1 SE3	Spectrum 1	1.0	0.3	30.5	1.1	0.5	0.6	66.0	100
	Spectrum 2	1.4	0.0	30.6	1.1	0.4	0.6	65.9	100
	Spectrum 3	1.4	0.1	30.6	1.0	0.5	0.6	65.9	100
	Mean	1.3	0.1	30.6	1.0	0.4	0.6	65.9	100
Msete1 SE4	Spectrum 1	1.5	0.0	30.7	1.3	0.3	0.5	65.5	100
	Spectrum 2	1.7	0.3	30.8	1.4	0.4	0.6	64.8	100
	Spectrum 3	1.4	0.1	30.8	1.3	0.4	0.6	65.4	100
	Mean	1.5	0.1	30.8	1.4	0.4	0.6	65.3	100
Msete1 SE5	Spectrum 1	2.1	0.1	31.0	0.7	0.3	0.6	65.1	100
	Spectrum 2	1.5	0.4	30.7	1.0	0.6	0.5	65.4	100
	Spectrum 3	2.1	0.5	30.9	0.9	0.7	0.5	64.4	100
	Mean	1.9	0.3	30.8	0.9	0.5	0.5	65.0	100
Nundu2 SE6	Spectrum 1	0.8	0.1	30.8	0.5	0.3	0.6	66.9	100
	Spectrum 2	1.5	0.2	30.9	0.4	0.2	0.6	66.2	100
	Spectrum 3	0.9	0.1	30.4	0.6	0.5	0.7	66.8	100
	Mean	1.1	0.1	30.7	0.5	0.4	0.6	66.6	100
Nundu2 SE7	Spectrum 1	1.5	0.4	30.5	0.5	0.7	0.5	65.9	100
	Spectrum 2	1.4	0.2	30.9	0.5	0.5	0.5	65.9	100
	Spectrum 3	1.0	0.4	30.6	0.5	0.7	0.4	66.4	100
	Mean	1.3	0.3	30.7	0.5	0.6	0.5	66.1	100
Nundu2 SE8	Spectrum 1	2.7	0.3	30.9	0.8	0.6	0.6	64.2	100
	Spectrum 2	2.3	0.3	31.0	0.7	0.4	0.6	64.7	100
	Spectrum 3	2.3	0.2	31.1	0.8	0.4	0.7	64.5	100
	Mean	2.4	0.3	31.0	0.8	0.5	0.6	64.4	100
Nundu2 SE9	Spectrum 1	2.0	0.1	30.8	0.5	0.4	0.6	65.7	100
	Spectrum 2	2.1	0.1	30.6	0.5	0.1	0.6	66.0	100
	Spectrum 3	2.7	0.2	30.5	0.4	0.3	0.4	65.5	100
	Mean	2.3	0.1	30.6	0.5	0.3	0.5	65.7	100
Nundu2 SE10	Spectrum 1	2.0	0.2	31.0	0.6	0.6	0.5	65.2	100
	Spectrum 2	2.1	0.0	31.2	0.6	0.3	0.5	65.3	100
	Spectrum 3	1.7	0.0	31.2	0.5	0.7	0.5	65.4	100
	Mean	1.9	0.1	31.1	0.6	0.5	0.5	65.3	100